PB86-195278

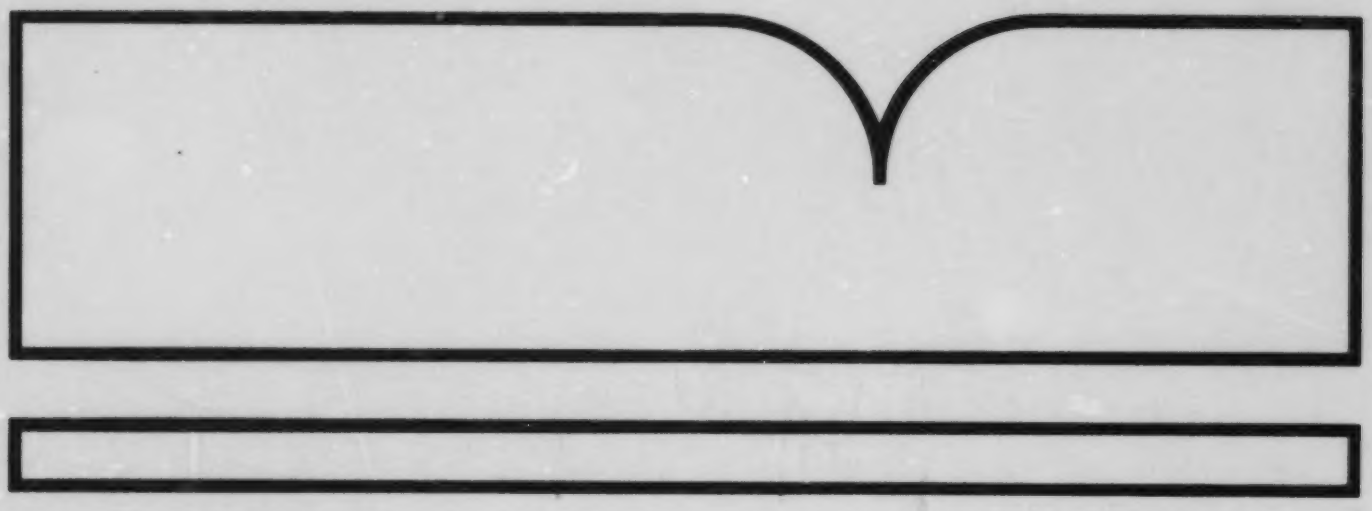
Coal Gasification
Environmental Data Summary
Trace Elements

Radian Corp., Austin, TX

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Apr 86



U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-195278

EPA/600/7-86/015e
April 1986

COAL GASIFICATION ENVIRONMENTAL DATA
SUMMARY: TRACE ELEMENTS

by

Larry J. Holcombe
Ronald D. Achord
Robert A. Magee
Robert M. Mann
RADIAN CORPORATION
P.O. Box 9948
Austin, TX 78766

EPA Contract No. 68-02-3137

Project Officer

William J. Rhodes
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

AIR AND ENERGY ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/7-86/015e		

4. TITLE AND SUBTITLE	5. REPORT DATE
Coal Gasification Environmental Data Summary: Trace Elements	April 1986
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) L. J. Holcombe, R. D. Achord, R. A. Magee, and R. M. Mann	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Radian Corporation P. O. Box 9948 Austin, Texas 78766	10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. 68-02-3137
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final; 9/84 - 12/85 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is William J. Rhodes, Mail Drop 62B, 919/541-2853.

16. ABSTRACT The report summarizes trace element measurements made at several coal gasification facilities. Most of the measurements were made as part of EPA's source testing and evaluation program on low- and medium-Btu gasification. The behavior of trace elements is discussed in light of their distribution from feed coal to various discharge, product, and by-product streams. This summary provides a basis for decisions concerning monitoring needs at coal gasification facilities. The stream flow data and trace element concentration measurements were typically not precise or accurate enough to make quantitative conclusions concerning trace element behavior in the gasifiers. However, some general trends in element distribution are apparent. Elements that consistently had more than 70% of their total inlet mass partition to the bottom ash or slag included Al, Ba, Co, K, U, W, and Zr. Other elements had consistently less than 70% of their mass partition to the bottom ash, and had significant mass flow in the overhead gas and aerosols. They included Sb, As, Br, Cd, Cl, Ge, I, Pb, Hg, Se, and Tl. Other elements measured in the gasifier output streams had varying behavior depending on the gasifier. Unknown controlling factors and the variability of the processes precluded comparisons between the trace element behavior in the different gasifiers.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Coal Gasification	Stationary Sources	13H
Coal	Environmental Assessment	21D
Metals		07B
Assessments	Trace Elements	14B
Chemical Analysis		07D

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	120
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

This report summarizes trace element measurements made at several coal gasification facilities. Most of the measurements were made as part of EPA's source testing and evaluation program on low-and medium-Btu gasification. The behavior of trace elements is discussed in light of their distribution from feed coal to various discharge, product, and by-product streams. This summary provides a basis for decisions concerning monitoring needs at coal gasification facilities.

The stream flow data and trace element concentration measurements were typically not precise or accurate enough to make quantitative conclusions concerning trace element behaviors in the gasifiers. However, some general trends in element distributions are apparent. Elements that consistently had more than 70 percent of their total inlet mass partition to the bottom ash or slag included aluminum, barium, cobalt, potassium, uranium, tungsten, and zirconium. Other elements consistently had less than 70 percent of their mass partition to the bottom ash, and had significant mass flow in the overhead gas and aerosols. They included antimony, arsenic, bromine, cadmium, chlorine, germanium, iodine, lead, mercury, selenium, and thallium. Other elements measured in the gasifier output streams had varying behaviors depending on the gasifier. Unknown controlling factors and the variability of the processes precluded comparisons between the trace element behaviors in the different gasifiers.

CONTENTS

		Page
Abstract		iii
Figures		vi
Tables		viii
1.	Introduction	1
2.	Conclusions	3
	Trace element distributions	4
	Environmental issues	6
3.	Summary Process Descriptions	8
	Summary and comparison of gasification operations	13
	Summary and comparisons of downstream processing operations	23
4.	Results and Discussion	31
	Quality Control	32
	Gasification	35
	Ash water	46
	Gas cleanup	51
References		63
Appendices		
A.	Mass balance data for coal gasification tests presented as percent of input	66
B.	Mass balance data for coal gasification tests presented as percent of total output	79
C.	Enrichment factor calculations for gasifier ash and cyclone dust	95
D.	Gasifier flow rate data	101

FIGURES

Number		Page
1.	Conceptual configuration of different gasifier bed types	18
2.	Comparative coal feedstock analyses, dry basis	20
3.	Comparative gasifier feed rates	21
4.	Comparative gasifier feed ratios	22
5.	Simplified block flow diagram of Chapman gasifier	24
6.	Simplified block flow diagram of Wellman-Galusha (Ft. Snelling) gasifier	24
7.	Simplified block flow diagram of Wellman-Galusha (Glen-Gery) gasifier	25
8.	Simplified block flow diagram of Riley gasifier	25
9.	Simplified block flow diagram of Foster-Wheeler/STOIC gasifier	26
10.	Simplified block flow diagram of Lurgi-type gasifier	26
11.	Simplified block flow diagram of KRW PDU gasifier	27
12.	Simplified block flow diagram of Koppers-Totzek (Modderfontein) gasifier	27
13.	Simplified block flow diagram of Koppers-Totzek (Ptolemais) gasifier	28

FIGURES (continued)

Number		Page
14.	Simplified block flow diagram of Texaco/Ruhrchemie gasifier.....	28
15.	Average elemental distribution of elements in product gas from fixed-bed gasifiers.....	42
16.	Enrichment factors for solid discharges and by-product streams for Lurgi-type gasifiers.....	57

TABLES

Number		Page
1.	Comparison of coal gasification facilities	10
2.	Trace element distributions in gasifier ash expressed as percent of input	38
3.	Boiling point for possible inorganic species during coal gasification	45
4.	Concentrations of trace elements in EP extracts of gasifier ash	47
5.	Comparison of ash and cyclone dust waters to water quality standards	49
6.	Elemental distributions in ash waters	50
7.	Comparison of wastewater blowdown to drinking water standards	52
8.	Cyclone dust enrichment factors	54
9.	Concentrations of trace elements in EP extracts of cyclone dust	59
10.	Comparison of trace element concentrations in product gases to TLVs	61
11.	Comparison of vaporous trace element concentrations in product gases to TLVs	62
A-1.	Trace element distribution in gasifier ash expressed as percent of input	67
A-2.	Trace element distribution in ash sluice water expressed as percent of input	69
A-3.	Trace element distribution in cyclone dust expressed as percent of input	71
A-4.	Trace element distribution in product gas expressed as percent of input	73

TABLES (continued)

Number		Page
A-5.	Trace element distribution in waste streams expressed as percent of input	75
A-6.	Trace element distribution in other streams expressed as percent of input	77
B-1.	Gasifier ash elemental distribution	81
B-2.	Ash sluice water elemental distribution	84
B-3.	Gasifier ash + sluice water elemental distribution	87
B-4.	Cyclone dust elemental distribution	90
B-5.	Product gas elemental distribution	93
C-1.	Gasifier ash enrichment factors	96
C-2.	Cyclone dust enrichment factors	99
D-1.	Chapman gasifier stream flow rate data	101
D-2.	Wellman-Galusha (Ft. Snelling) gasifier stream flow rate data	102
D-3.	Wellman-Galusha (Glen-Gery) stream flow rate data	103
D-4.	Riley gasifier stream flow rate data	104
D-5.	Foster-Wheeler/STOIC gasifier stream flow rate data	105
D-6.	Lurgi-type gasifier stream flow rate data	106
D-7.	KRW PDU gasifier stream flow rate data	107
D-8.	Koppers-Totzek gasifier stream flow rate data	108
D-9.	Texaco gasifier stream flow rate data	109

SECTION 1

INTRODUCTION

The U.S. EPA conducted numerous data acquisition studies at synthetic fuel facilities including:

- Chapman (low-Btu),
- Wellman-Galusha (low-Btu),
- Riley Gas Producer (low-Btu),
- Foster-Wheeler/STOIC (low-Btu),
- Koppers-Totzek (medium-Btu),
- Lurgi-type (medium-Btu), and
- Texaco (medium-Btu) (jointly funded by EPA, TVA and EPRI).

In these programs, data on the characteristics of process and emission/effluent streams were obtained.

The objective of this summary report is to present distributions of trace elements, and other minor and major elements, from measurements made at the coal gasification facilities tested during the EPA studies (1 - 8), and from Kellogg-Rust/Westinghouse (KRW) (9), Synthane (10), and Lurgi (SASOL) (11)

process characterizations. Trace elements refers to those chemical elements not major constituents of the coal mineral matter. The analytical data presented here include major and trace elements, however, trace elements are emphasized in the evaluations.

Considerable research has been conducted to define trace element distribution and emissions from coal combustion facilities. A number of groups have researched the volatility and distribution of elements in specific ash fractions and other discharge streams at coal combustion plants (12-21).

The data from the source test and evaluation studies were evaluated, and general behavior trends are presented in this report. The methods used in sampling and analyzing trace elements in the gasifier streams varied only slightly from one program to the next. Solid samples were collected as grab samples or composites of several grab samples. Gas phase samples for trace elements analysis were collected by drawing gas from the stream through a nozzle, probe, and sample line and then a series of impingers. The impingers contained either alternating acidic or basic solutions or an ammonium persulfate solution.

Trace elements were analyzed using spark source mass spectrometry (SSMS), inductively coupled plasma emission spectrometry (ICP), and atomic absorption spectrometry (AAS). At Wellman-Galusha, Riley and STOIC all three analytical techniques were used. At Chapman, SSMS was the sole analytical technique, and ICP and AAS were used for the Lurgi-type (Kosovo) and Texaco source testing. Wide variations may exist between trace element behaviors in the various processes; however, the general trends reported here will serve as a guideline for further source testing or discharge stream monitoring considerations.

The next section presents the conclusions from the evaluation of the data. Section 3 summarizes the processes considered, and Section 4 presents data summaries. Detailed tabulations of trace element data are contained in the Appendices.

SECTION 2

CONCLUSIONS

Data from the following gasification processes were evaluated for trace element distributions:

- Chapman (1),
- Wellman-Galusha (Glen-Gery) (2),
- Wellman-Galusha (Ft. Snelling) (3),
- Riley (4),
- Foster Wheeler/STOIC (5),
- Koppers-Totzek (6),
- Lurgi-type (7), and
- Texaco (8).

In addition, data collected at the KRW PDU(9), Synthane Pilot Plant (10) and Lurgi (SASOL) (11) were included for comparison.

TRACE ELEMENT DISTRIBUTIONS

Trace elements enter the gasification process in the coal feed. In the gasifier the fraction of coal that does not combust moves to the bottom of the

gasifier as ash or slag. The gas produced contains vaporous trace elements as well as dust and aerosols containing trace elements.

The flow measurements and concentration (mass) measurements made in these gasification tests had inherent imprecisions. Comparisons between the total mass flow of individual elements entering the gasifier in the coal and the sum of the mass flows exiting the gasifier confirmed this precision in many trace element measurements. A ratio of mass flow in/mass flow out should be unity for a perfect mass balance. Actual ratios were often much greater or less than unity, depending on the element or analytical method. Despite these imprecisions, which include more than just analytical imprecision, general trends in trace element distribution and behavior were apparent. These trends are noted below:

- The following elements consistently had more than 70 percent of their total inlet mass partition to the bottom ash or slag (for all gasifiers evaluated):

Aluminum	Uranium
Barium	Tungsten
Cobalt	Zirconium
Potassium	

- The following elements had consistently less than 70 percent of their mass partition to the bottom ash. Where overhead stream measurements were made, these elements had greater than 20 to 30 percent mass flow in the overhead gas and the dust and aerosols entrained with the gas:

Antimony	Chlorine	Mercury
Arsenic	Germanium	Selenium
Bromine	Iodine	Thallium
Cadmium	Lead	

Data were not precise enough nor consistent enough to be able to make any conclusions comparing the differences in trace element behavior between different gasifiers.

Overhead gas streams are routed through control devices to remove undesirable constituents such as dust, heavy tar, acid gases, and organic gases. By-products, such as tar, oil, naphtha, and others may also be removed.

The tendency for trace elements to distribute in the dust captured in cyclones was evaluated by examining data from four fixed-bed gasifier tests (2, 3, 4, 5). The following elements were highly enriched[1] (relative to the coal ash) in the cyclone dust:

Antimony	Germanium
Arsenic	Lead
Bismuth	Mercury
Cadmium	Tin
Gallium	

Additionally, thallium and zinc were enriched in the cyclone dust from the four fixed-bed gasifiers, and nickel was enriched in the gas particulate matter from KRW.

Trace element concentrations were monitored in several gas cleanup waste and by-product streams at the Lurgi-type (Kosovo) gasifier (7). The gas cleanup streams monitored, in order of successive downstream location, were heavy tar, light tar, and medium oil. Six of the elements measured during a test at the Lurgi-type (Kosovo) gasifier showed slight depletion in the gasifier ash and a generally increasing enrichment factor in the cleanup streams successively downstream. In other words, these elements were more highly enriched in the medium oil than in either the light tar or heavy tar.

[1] $\text{Enrichment factor} = \dfrac{\text{Concentration of element in stream/Concentration of ash in stream}}{\text{Concentration of element in coal/Concentration of ash in coal}}$

These elements were:

Lead	Arsenic
Chromium	Selenium
Strontium	Copper

ENVIRONMENTAL ISSUES

Solid Waste

The gasifier ash or slag carries the greatest mass of trace elements from the process. Cyclone dust, also a solid waste stream, is another vehicle for discharge of trace elements from the gasifier. The ultimate fate of trace elements carried from the process in the solid waste streams is a function of the method of disposal. Trace elements in the gasifier ash/slag or cyclone dust may enter the environment as a result of leaching by run-off waters from surface disposal sites or by leaching from landfills into ground water. Trace element concentrations in mild acidic leachings (RCRA EP Toxicity Test) of gasifier ash and cyclone dust were compared to RCRA maximum permissible concentrations[2]. All solids tested were nontoxic by the EP Toxicity criteria.

Aqueous Discharges

Water which is used to quench or transport the ash or cyclone dust is another vehicle for discharge of trace elements from the gasifier. The concentration of trace elements in the ash water is dependent upon the form of the element in the ash, the length of time the ash is in contact with the water, and the physical characteristics of the ash. Concentrations of trace elements in ash or cyclone dust sluice waters were compared to the strictest drinking and irrigation water quality criteria. Under normal procedures these water quality criteria would not be used in a direct comparison to assess environmental risk. Some consideration for dilution or the eventual discharge of the water would be made prior to establishing pollutant discharge limits.

---

[2] EP Toxicity Test, "Test Methods for Evaluating Solid Waste", EPA SW-846, U.S. Environmental Protection Agency, Washington DC, 1982.

However, the criteria provide a relative basis to identify elements which may be of environmental concern in the ash waters. Trace elements that exceeded the strictest criteria at one or more of the plants were barium, boron, chromium, mercury, manganese, and molybdenum.

Gaseous Discharges

Gaseous discharges with trace element concentrations of possible environmental concern are fugitive emissions (pokehole gases, coal hopper vent gases, and other vent gases). Only a few fugitive emissions were measured directly. However, it can be assumed that fugitive emissions will be similar in chemical composition to the product gas, with the exception of different particle loading. Product gas concentrations of trace elements from four fixed-bed gasifiers were compared to work place TLV's (threshold limit values[3]) to indicate potential environmental and health concerns. In this direct comparison of product gas concentrations to TLV's consideration has not been given to dilution by work place air or loss, through settling, of entrained particulate matter. Elements which exceeded the TLV in at least one stream included aluminum, arsenic, barium, beryllium, cadmium, copper, iron, lead, mercury, selenium, silver, and tellurium. All but arsenic, copper, lead, silver, and tellurium exceed the TLV solely due to their particulate matter contribution.

Vaporous trace element concentrations were measured in the gas phase only at the KRW PDU. Considerably fewer elements were analyzed at KRW than at the four fixed-bed gasifiers. Only nickel in the subbituminous coal test exceeded the TLV.

[3]As suggested by the American Conference of Governmental Industrial Hygienists, "TLV for Chemical Substances and Physical Agents in the Work Environment", ACGIH, ISBN: 0-936712-45-7, Cincinnati, OH, 1983.

SECTION 3

PROCESS DESCRIPTIONS

INTRODUCTION

This section presents brief descriptions and comparisons of the coal gasification facilities for which data are presented in this report. The following types of gasifiers and facilities are included:

- Chapman low-Btu industrial gasifiers at Kingsport, Tennessee;
- Wellman-Galusha low-Btu gasifiers at the Bureau of Mines Twin Cities Metallurgy Research Center, Fort Snelling, Minnesota, and Glen-Gery Brick Company, York, Pennsylvania;
- Riley Gas Producer low-Btu gasifier at Worcester, Massachusetts;
- Foster-Wheeler/STOIC low-Btu industrial gasifier at the University of Minnesota, Duluth (UMD);
- Lurgi-type medium-Btu commercial gasifiers at Kosovo, Yugoslavia;
- Kellogg-Rust/Westinghouse (KRW) medium-Btu gasifier PDU at Madison, Pennsylvania;
- Koppers-Totzek medium-Btu commercial gasifiers at Modderfontein, South Africa;

- Koppers-Totzek (GKT) medium-Btu commercial gasifier at Ptolemais, Greece; and

- Texaco medium-Btu demonstration gasifier at the Ruhrkohle/Ruhrchemie facility in Oberhausen-Holten, Federal Republic of Germany.

Table 1 presents a summary of the features of the coal handling/preparation, coal feeding, gasification, and downstream processes (including gas cleanup and ash removal/handling) present at each facility. The similarities and differences will be discussed in more detail later; however, some of the salient differences between processes are summarized below:

- Oxygen versus Air-Injection: Gasifiers that use air as their source of oxygen produce a gas having a lower calorific value than those that use pure or nearly pure oxygen. This is due to the nitrogen diluent present in air. Chapman, Wellman-Galusha, Riley, and Foster-Wheeler/STOIC gasifiers are of the so-called "low-Btu" type, while the Koppers-Totzek and Texaco gasifiers both produce "medium-Btu" gas. The Lurgi and KRW gasifiers can be operated in either mode; the data presented here were obtained on systems producing medium-Btu gas.

- Bed Type: There are three principal gasifier bed types: moving-bed, fluidized-bed, and entrained-bed. Moving-bed (sometimes referred to as fixed-bed) gasifiers feature a layer of coal which is generally supported on a grate through which air (or oxygen) and steam are passed. In thin bed systems, less than a 0.5 m layer of coal is maintained on the coal grate. In thick bed systems, bed depths of 2 to 5 m are more typical. The direction of movement of the coal relative to the gas is countercurrent. In fluidized-bed gasifiers the upward velocity of the gas stream is such that the fluid drag forces nearly balance the downward forces due to the weight of the coal/ char particles. The particles act

TABLE 1. COMPARISON OF COAL GASIFICATION FACILITIES

	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster-Wheeler/ STOIC
COAL HANDLING					
Receive prepared coal	X	X	X	X	X
Crush/pulverize					
Screen		X			X
Thermal drying					
Slurrying					
Air classifying					
COAL FEEDING					
Lock hoppers		X	X	X	X
Screw feed/entrainment					
Slurry pumping					
Barrel valve	X				
GASIFICATION					
Atmospheric (A)/Pressurized (P)	A	A	A	A	A
Moving- (M)/Fluid- (F)/Entrained-bed (E)	M	M	M	M	M
Thin bed (T)/Deep bed (D)	T	D	D	T	D
Slagging (S)/Agglomerating (A)/ Dry ash (D)	D	D	D	D	D
Single-stage (S)/Two-stage (T)	S	S	S	S	T
Cocurrent (C)/Countercurrent (CC)	CC	CC	CC	CC	CC
Air blown (A)/O_2 blown (O)	A	A	A	A	A
GAS CLEANUP					
Cyclones	X	X	X	X	X
ESP					X
Quench/Scrubbing	X				
Acid gas removal					
ASH REMOVAL/HANDLING					
Lockhoppers					
Ash plow	X			X	X
Slide valve		X	X		
Water quench	X	X	X	X	X
Conveyor/Drag chain	X				X

(continued)

TABLE 1. COMPARISON OF COAL GASIFICATION FACILITIES (Continued)

	Lurgi-type (Kosovo)	KRW PDU	Koppers-Totzek (Modderfontein)	Koppers-Totzek (Ptolemais)	Texaco (Ruhrchemie)
COAL HANDLING					
Receive presized coal					
Crush/pulverize	X	X	X	X	X
Screen	X				
Thermal drying	X	X	X	X	
Slurrying					X
Air classifying		X			
COAL FEEDING					
Lock hoppers	X	X			
Screw feed/entrainment			X	X	
Slurry pumping					X
Barrel valve					
GASIFICATION					
Atmospheric (A)/Pressurized (P)	P	P	A	A	P
Moving- (M)/Fluid- (F)/Entrained-bed (E)	M	F	E	E	E
Thin bed (T)/Deep bed (D)	D	D	-[a]	-[a]	-[a]
Slagging (S)/Agglomerating (A)/Dry ash (D)	D	A	S	S	S
Single-stage (S)/Two-stage (T)	S	S	S	S	S
Cocurrent (C)/Countercurrent (CC)	CC	CC	C	C	C
Air blown (A)/O_2 blown (O)	O	O	O	O	O
GAS CLEANUP					
Cyclones		X			
ESP			X	X	
Quench/Scrubbing	X	X	X	X	X
Acid gas removal	X		X	X	X
ASH REMOVAL/HANDLING					
Lockhoppers	X	X			X
Ash plow					
Slide valve					
Water quench	X		X	X	X
Conveyor/Drag chain	X		X	X	X

[a]Not applicable.

as if they were a turbulent fluid. In entrained-bed gasifiers, the coal and gases move in the same direction (co-current). Of the gasifiers represented here, only the KRW is a fluidized-bed gasifier; entrained-bed gasifiers include the Koppers-Totzek and Texaco gasifiers. All the rest are of the fixed-bed type.

- Single-stage versus Two-stage: In single-stage gasifiers, the raw product gas is taken off at a single location. In two-stage gasifiers, two separate raw product gas streams are generated. In a fixed-bed, two-stage design the upper gas product is richer in heavier hydrocarbon gases and aerosols formed by the release of coal volatile matter and water vapor resulting from the release of moisture in the feed coal. The lower gas product is richer in lighter combustible gases such as carbon monoxide and hydrogen. The only two-stage gasifier presented here is the Foster-Wheeler/ STOIC gasifier.

- Atmosphere Pressure versus Elevated Pressure: Operation at elevated pressure allows the use of smaller vessels for equivalent gas production. Increased partial pressures of reactive gases may increase reaction rates and/or alter reaction equilibria in both the gasifier and in downstream units. Additional effects of pressurized operation include:

  --reduced needs for compression of raw gas prior to downstream treatment units (e.g., physical absorption type acid gas removal processes) or prior to injection into a pipeline transmission system.

  --generation of flash gases from depressurization of by-product liquids, resulting in an additional waste gas stream.

Of the gasifiers considered here, only three were operated at elevated pressure; the Lurgi-type (Kosovo), KRW, and Texaco (Ruhrkohle/Ruhrchemie) gasifiers. The rest were operated at or near atmospheric pressure.

The remainder of this process description section consists of two subsections: the first discusses and compares the gasification processes (including coal preparation and coal feeding), while the second deals with downstream processing operations.

SUMMARY AND COMPARISON OF GASIFICATION OPERATIONS

Coal gasification involves the conversion of coal to gaseous species which can be burned as fuels or which can be used as feedstocks in the formation of fuels or other products. There are several general types of phenomena which occur during coal gasification which are common to all processes. These include coal drying and devolatilization, gasification, oxidation (or combustion), water-gas shift, volatilization and reaction of coal sulfur and nitrogen, and production of unreacted residuals (ash). Each of these may occur in different areas of the gasification reactor depending on the method used to contact the coal and the reactant gases.

Drying and Devolatilization

As the coal is heated, moisture is given off and the volatile fraction undergoes pyrolysis (i.e., thermal decomposition). The composition of the volatiles (some of which may be liquids or even solids at ambient conditions) depends on a number of factors including coal rank, coal particle thermal history (e.g., heating rate, duration of heating, and final temperature reached), and the composition and pressure of the reactant gas. Anthracite, for example, gives off relatively little volatile matter compared with bituminous coal or lignite. If devolatilization occurs at relatively low temperatures, the volatile fraction contains appreciable amounts of tar

and oil aerosols. If devolatilization occurs at higher temperatures, these tars and oils are largely converted, by further pyrolysis into lighter hydrocarbons, methane, hydrogen, carbon monoxide, and carbon dioxide.

Gasification

In the gasification zone, various reactions occur between the carbon in the coal and the hot gases present in the oxidation zone. The principal gasification reactions of interest are:

$$C + CO_2 + \text{heat} \longrightarrow 2CO$$

$$C + H_2O + \text{heat} \longrightarrow CO + H_2$$

$$C + 2H_2 \longrightarrow CH_4 + \text{heat}$$

As can be seen, the primary products of gasification are carbon monoxide, hydrogen, and methane. The energy required by the first two reactions is furnished by the sensible heat of the gases leaving the oxidation zone. The extent to which these competing reactions proceed to completion depends on factors such as pressure, temperature, residence time, and reactant concentrations.

Oxidation (Combustion)

Oxidation involves the heterogeneous reaction between coal carbon and oxygen to produce CO and CO_2:

$$C + O_2 \longrightarrow CO_2 + \text{heat}$$

$$C + 1/2\ O_2 \longrightarrow CO + \text{heat}$$

These reactions result in the release of energy that allows the gasification reactions to proceed. The ratio of carbon monoxide to carbon dioxide formed in the oxidation zone depends on the oxygen partial pressure and the temperature. If excess oxygen is present, some of the carbon monoxide will be converted to CO_2 by gas phase oxidation.

In addition, in entrained-bed gasifiers and some fluidized-bed gasifiers where devolatilization occurs in an oxygen-rich environment, tars and oils and other organics are also oxidized in the gas phase, forming carbon monoxide, carbon dioxide, and hydrogen.

Water-Gas Shift

An important gas-phase reaction occurring in the gasifier involves the equilibrium among carbon monoxide, carbon dioxide, hydrogen, and water vapor:

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

The composition of the raw product leaving the gasifier is significantly influenced by this equilibrium. High temperature favors the formation of carbon monoxide and water vapor. The relative partial pressures of the various reactants also influence the equilibrium composition.

Sulfur and Nitrogen Reactions

Coal contains varying amounts of sulfur and nitrogen. Significant reaction products formed from these elements during gasification include ammonia, hydrogen cyanide, hydrogen sulfide, carbonyl sulfide, and other organic sulfur species (such as mercaptans). The quantities of such species formed depend on a number of factors including coal sulfur and nitrogen content, temperature, pressure, and hydrogen concentration in the gas. The ratio of carbonyl sulfide to hydrogen sulfide is a particularly important

concern because this ratio can affect the selection, design, and performance of downstream acid gas removal and sulfur recovery processes. As with the water-gas shift reactions discussed above, the ratio of COS to H_2S in the raw gas is affected by the steam and carbon dioxide content of the gas due to the chemical equilibrium which is maintained at high temperatures among these four species:

$$H_2S + CO_2 \rightleftharpoons COS + H_2O$$

Similar relationships may also hold for nitrogen species such as ammonia and hydrogen cyanide.

Solid Waste

Coal contains substantial quantities of nonreactive mineral matter which remains after the coal has been gasified. The resulting solid waste will be in the form of ash or solidified slag droplets, depending primarily on the reactor operating temperature and the ash fusion point. Fixed-bed gasifiers can be operated to produce either a "dry", unfused ash (low-temperature operation) or a fused slag by-product (high-temperature operation). Entrained-bed gasifiers operate at high temperatures and produce a slag by-product. Some fluidized-bed gasifiers operate at a temperature at which the ash particles are soft and sticky and form agglomerates that are removed from the gasifier. Some of the mineral matter components may also be volatilized; the extent to which this occurs depends on the temperature and the chemical forms in which these compounds are found in the coal.

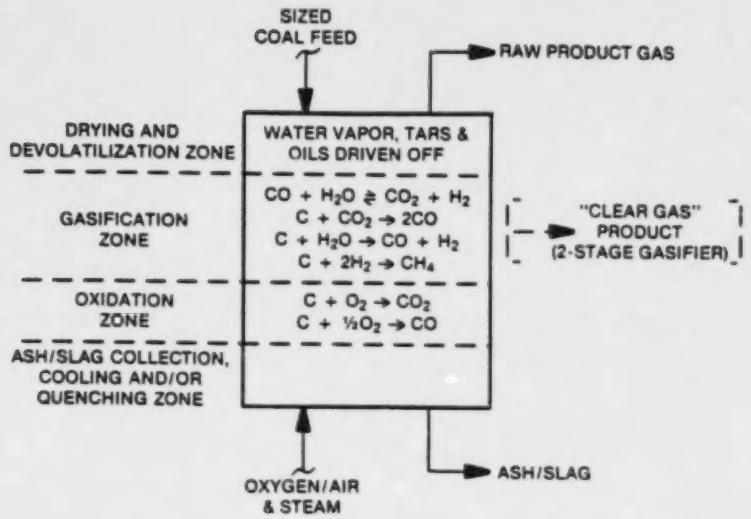
The susceptibility to leaching of the species remaining in the ash or slag is also likely to vary depending on their solubility and the ease with which water can penetrate the solid. For example, fused slags are less subject to leaching than more porous ash particles.

Figure 1 shows the conceptual zones into which fixed-bed, fluidized-bed, and entrained-bed gasifiers may be divided. Note that in the fixed-bed and fluidized-bed gasifiers, the relative direction of gas and solid flows is countercurrent, while it is co-current in the entrained-bed gasifier. Also note the differences in the order of the various reaction zones.

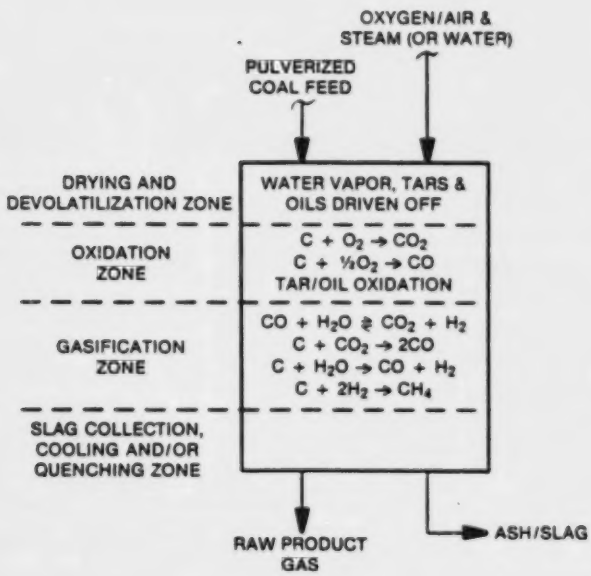
Associated closely with the gasification operation are the equipment and operations required to prepare the coal and feed it into the gasifier vessels. In the case of most small, low-Btu gasification facilities, very limited coal preparation is performed. These facilities typically gasify coal which has been sized prior to its delivery to the site. Some screening of the coal for removal of fines is performed at two of the low-Btu facilities tested (Wellman-Galusha at Fort Snelling, and Foster-Wheeler/STOIC at UMD). As-received coal is crushed and sized on site at all of the medium-Btu facilities considered in this report. At the Lurgi-type (Kosovo), KRW PDU, and Koppers-Totzek (Modderfontein and Ptolemais) facilities, coal drying is performed. The entrained-bed gasifiers (Koppers-Totzek and Texaco) require more extensive preparation (crushing and pulverizing) to produce the finely divided coal feed used in these gasifiers.

A variety of methods are used to feed the prepared coal into the gasifiers. Lockhoppers are used with Wellman-Galusha, Riley, Foster-Wheeler/STOIC, Lurgi and KRW gasifiers. At the Chapman gasifier facility, coal is fed by means of a rotary feeding device known as a barrel valve. In the GKT gasifier, coal is augered out of a storage vessel and transported to the gasifier in a heated stream of steam and oxygen using a screw conveyor. The Texaco gasifier utilizes a slurry system in which pulverized coal is mixed with water, preheated, and pumped into the gasifier vessel.

Figures 2 through 4 summarize coal composition, gasifier feed rates, and reactant ratios for each of the gasification facilities. Flow rates are shown on a "per gasifier" basis to facilitate comparisons. The reactant ratios were calculated based on the reported feed rates. For the air-blown



FIXED BED,
COUNTERCURRENT GASIFIER



ENTRAINED-BED,
CO-CURRENT GASIFIER

Figure 1. Conceptual configurations of different gasifier bed types.

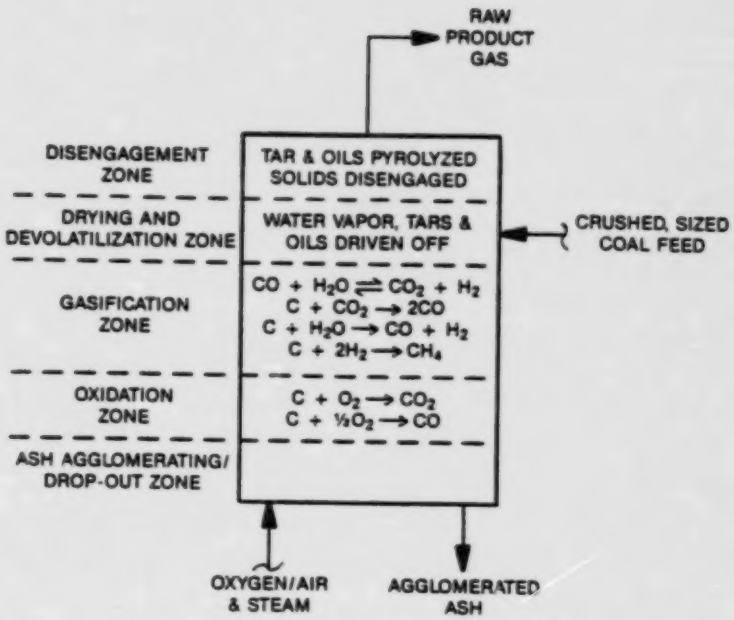
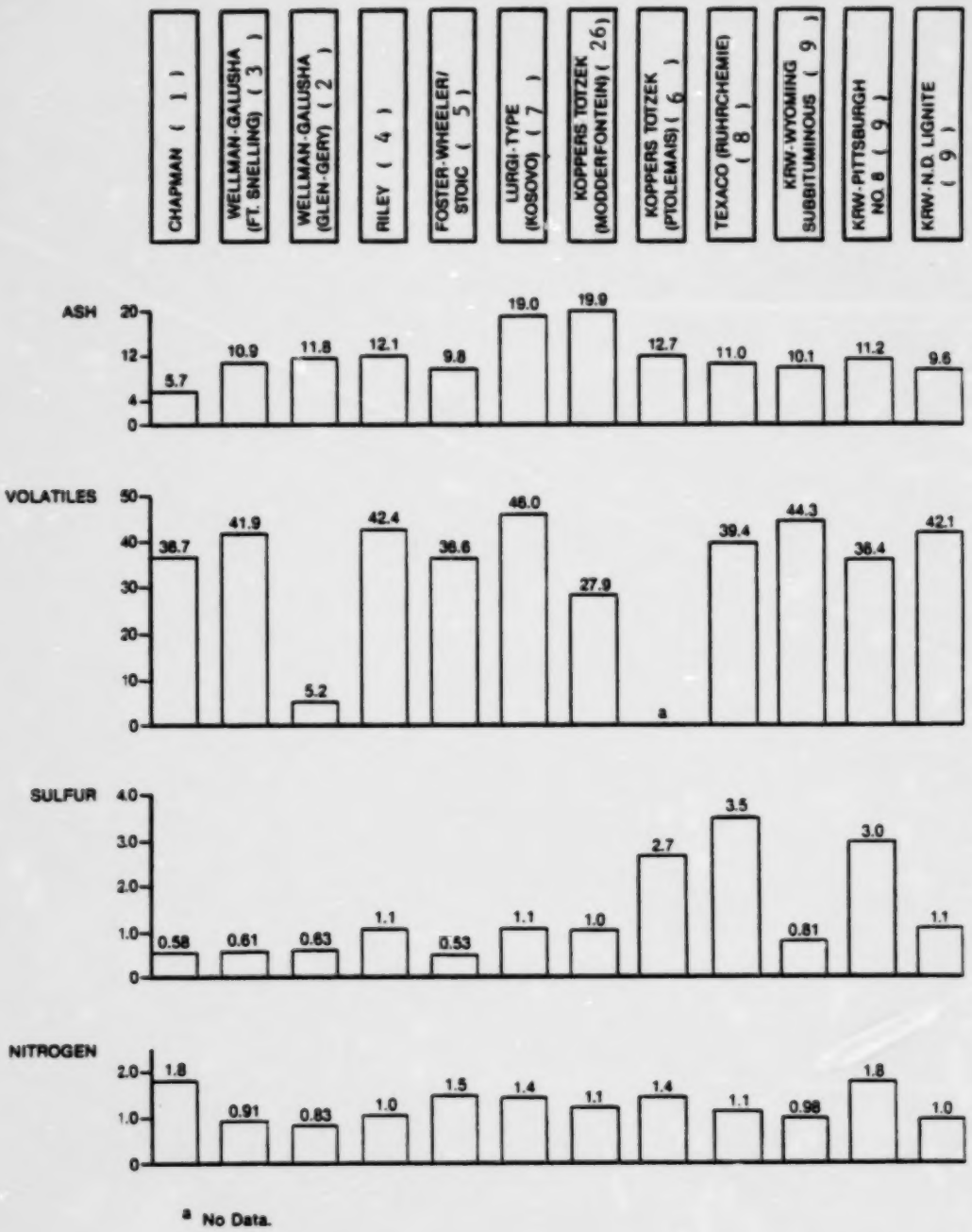
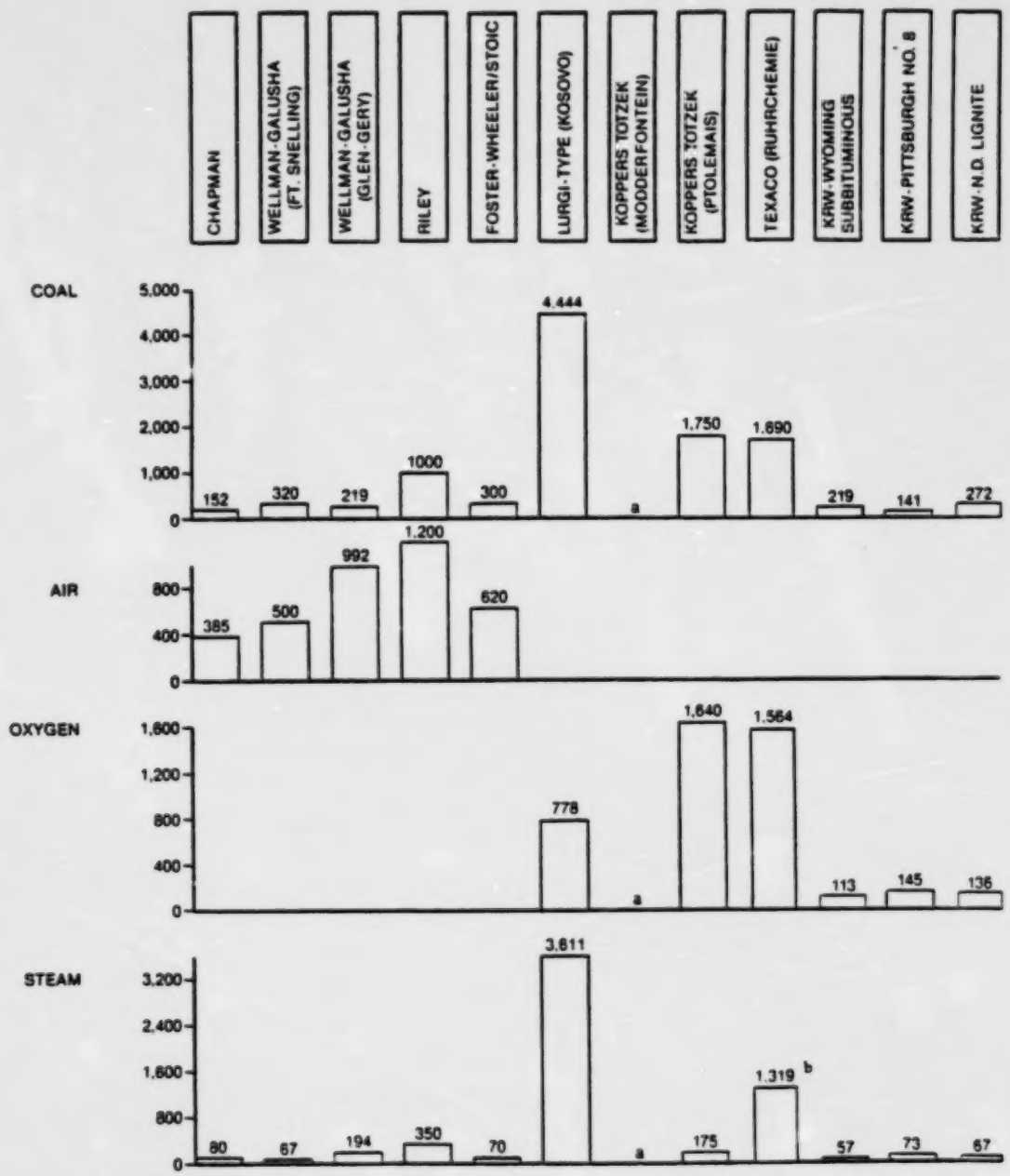


Figure 1. (Continued)



[a] No Data.

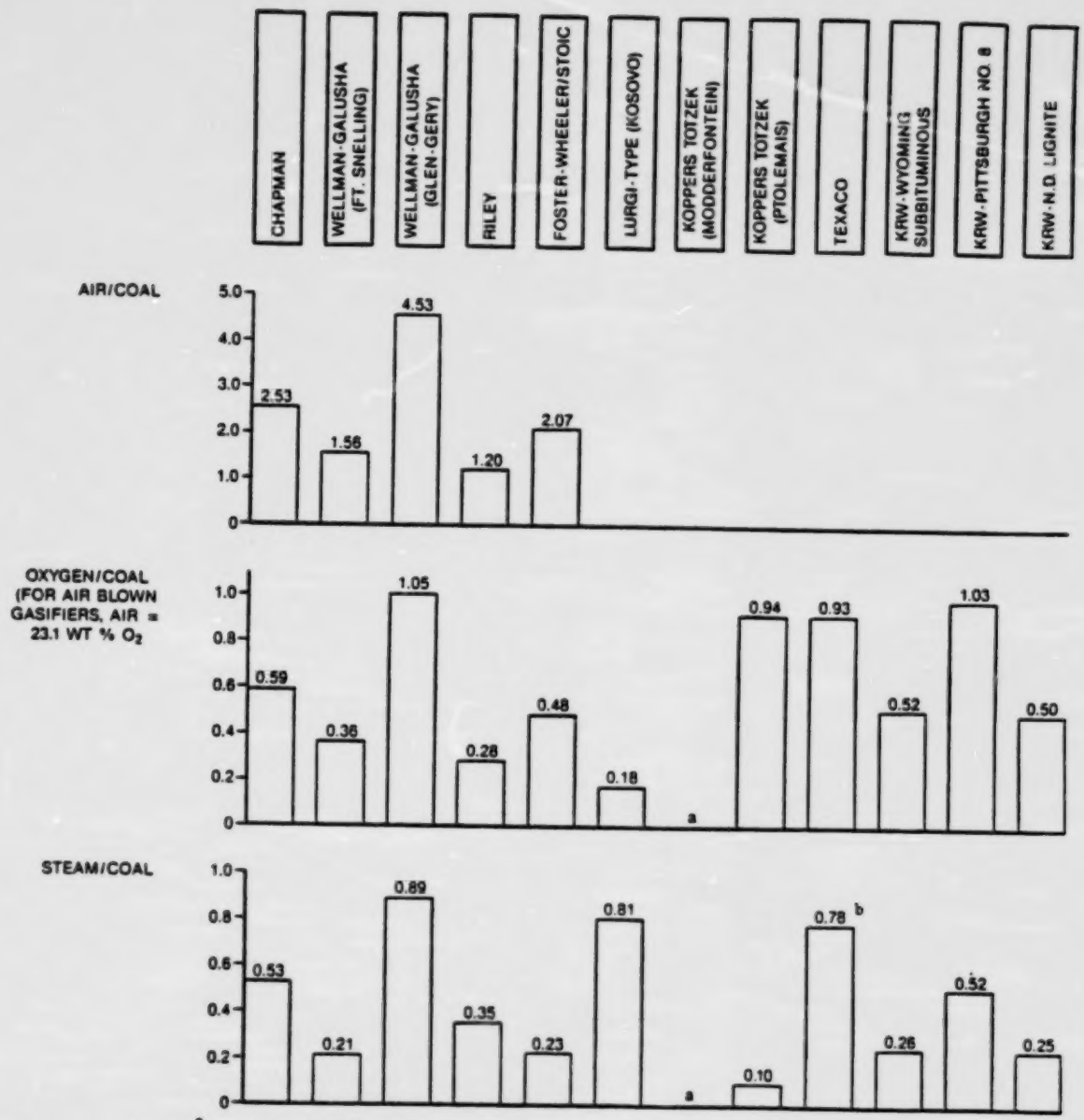
Figure 2. Comparative coal feedstock analyses, dry basis, wt %.



[a]No data available.

[b]For the Texaco Gasifier Only, the Steam Flow Rate is Taken as the Fresh Makeup Slurry Water, Coal Moisture, and Water in Additive and Flocculant.

Figure 3. Comparative gasifier feed rates, g/sec-gasifier.



[a]No data available.

[b]For the Texaco Gasifier Only, the Steam Flow Rate is Taken as the Fresh Makeup Slurry Water, Coal Moisture, and Water in Additive and Flocculant.

Figure 4. Comparative gasifier feed ratios, kg/kg.

gasifiers, the oxygen to coal ratio was calculated based on an oxygen content of 23.1 percent by weight for air.

SUMMARY AND COMPARISON OF DOWNSTREAM PROCESSING OPERATIONS

Processing operations downstream of gasification are needed to perform various functions including:

- Removal of entrained particulates (fly ash, tar, oil, etc.),
- Removal of gaseous contaminants (primarily sulfur and nitrogen species),
- Cooling of the raw product gas,
- Handling and disposal of solid wastes,
- Treatment and disposal of wastewater,
- Recovery of by-products (e.g., sulfur, ammonia, organics),
- Control of air pollutants, and
- Upgrading of the raw gas.

All of these processing operations are not present in all gasification facilities. Those found in the gasification facilities included in this report were shown in Table 1. Figures 5 through 14 are simplified block flow diagrams of these facilities. The major processing units and streams present in each of the facilities are shown, together with stream temperature data obtained at the time the facilities were characterized. Those streams for which composition and/or flow rate data were obtained are also

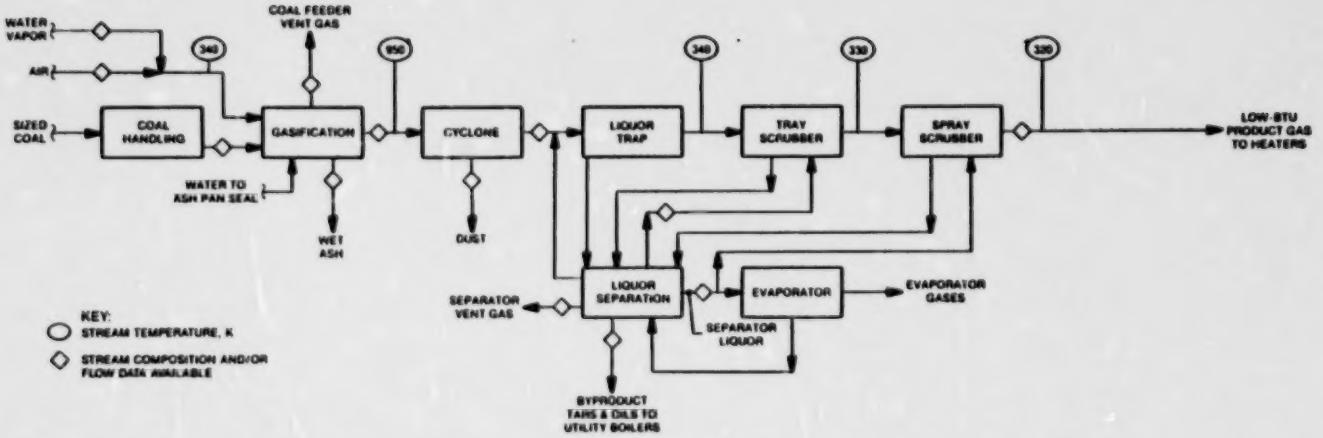


Figure 5. Simplified block flow diagram of Chapman gasifier.

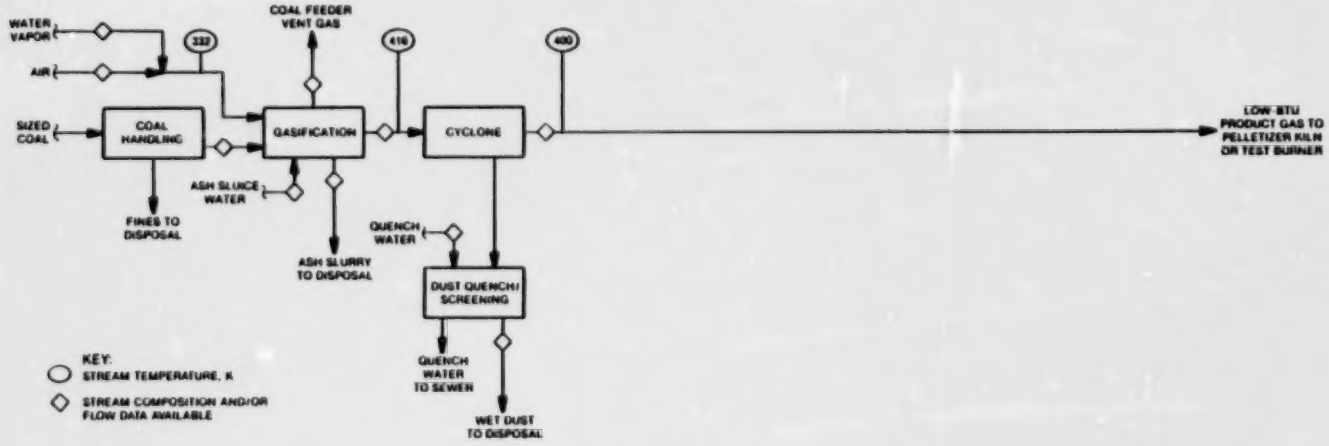


Figure 6. Simplified block flow diagram of Wellman-Galusha (Ft. Snelling) gasifier.

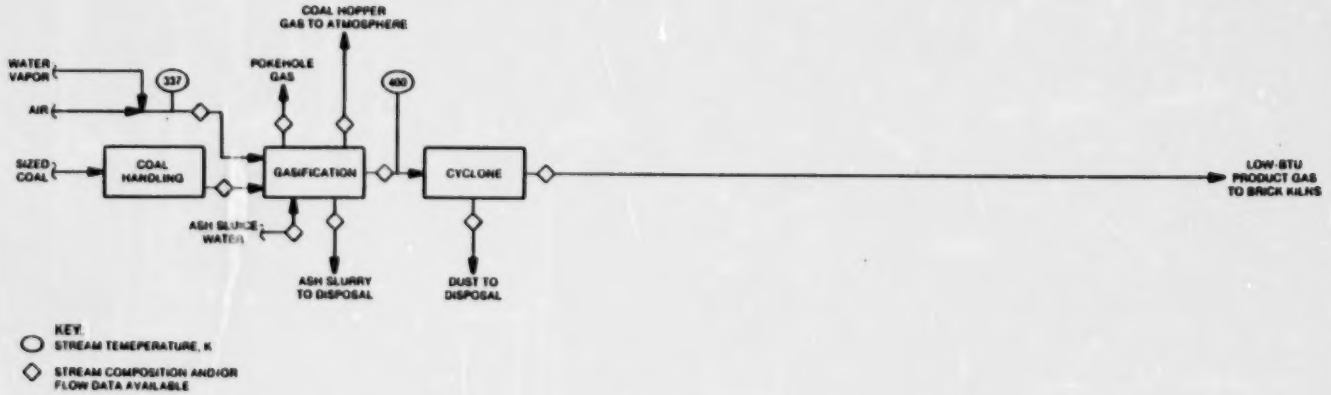


Figure 7. Simplified block flow diagram of Wellman-Galusha (Glen-Gery) gasifier.

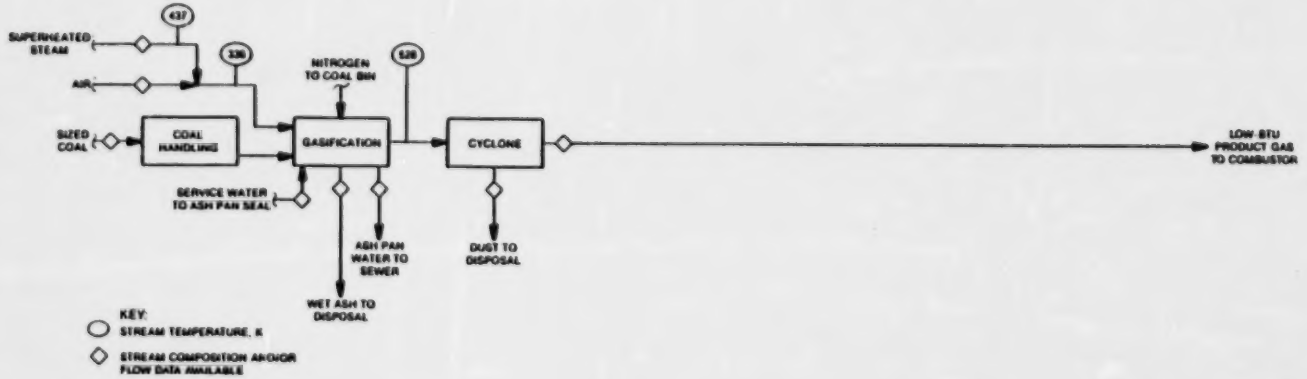


Figure 8. Simplified block flow diagram of Riley gasifier.

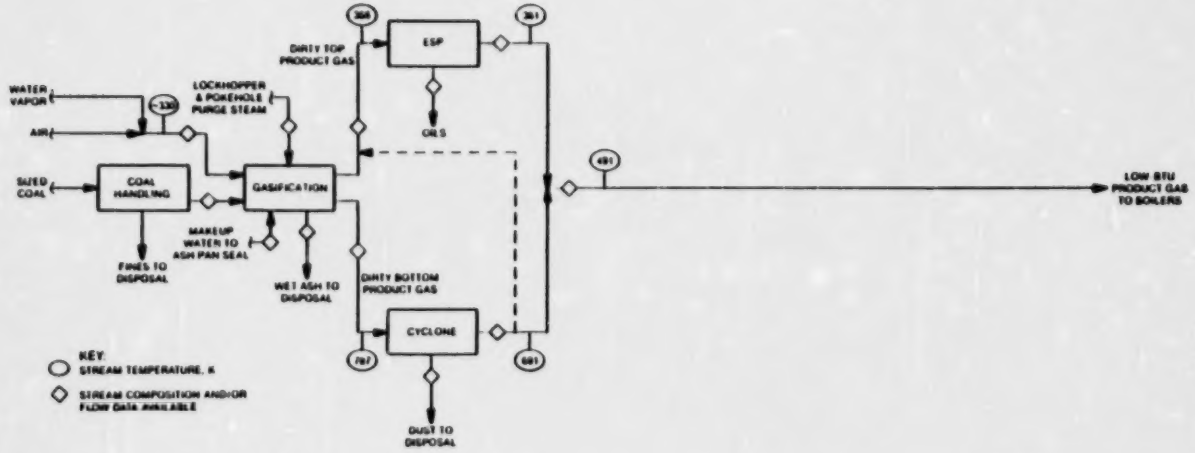


Figure 9. Simplified block flow diagram of Foster-Wheeler/STOIC gasifier.

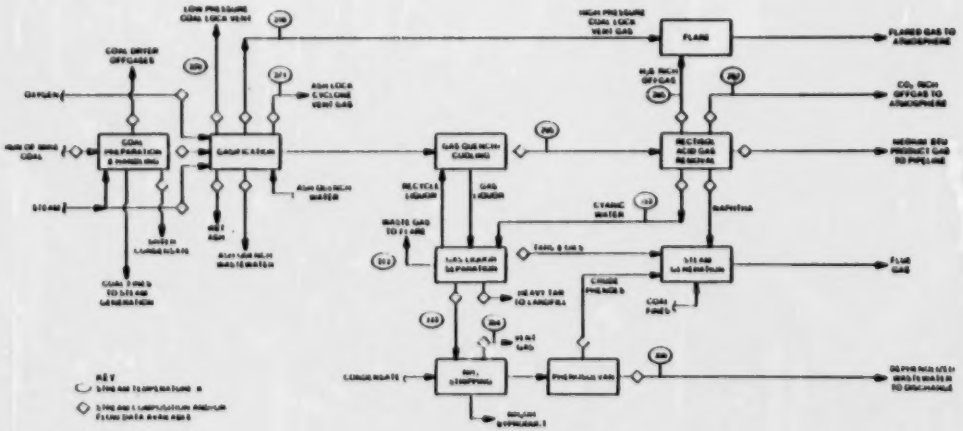


Figure 10. Simplified block flow diagram of Lurgi-type gasifier.

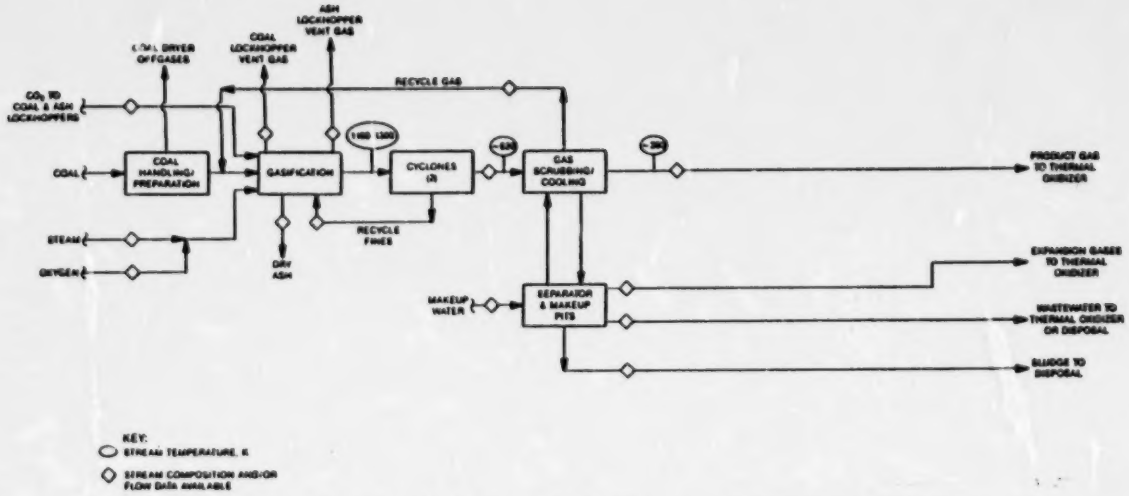


Figure 11. Simplified block flow diagram of KRW PDU gasifier.

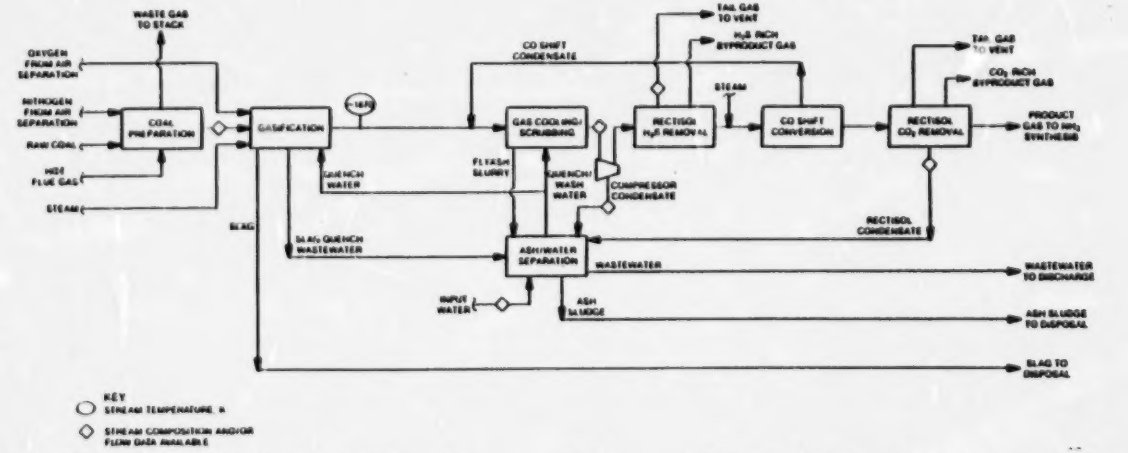


Figure 12. Simplified block flow diagram of Koppers-Totzek (Modderfontein) gasifier.

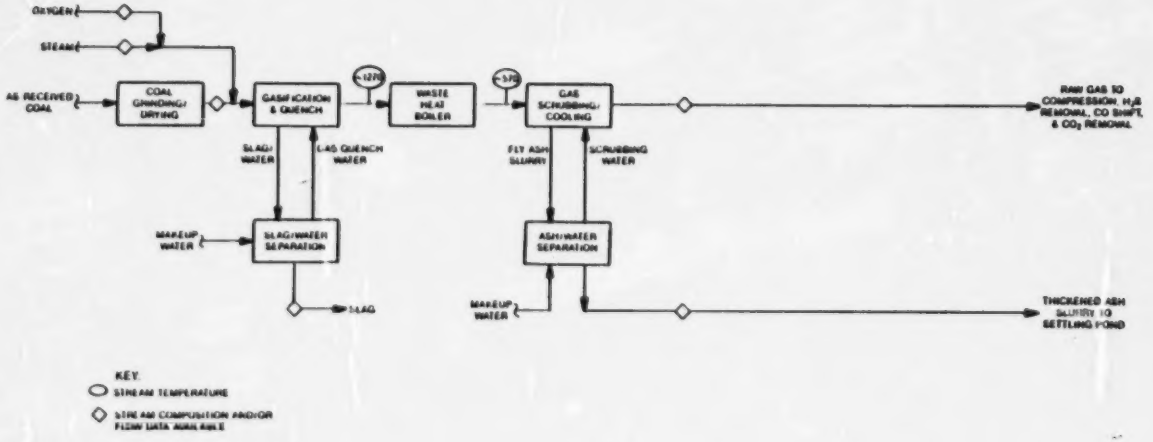


Figure 13. Simplified block flow diagram of Koppers-Totzek (Ptolemais) gasifier.

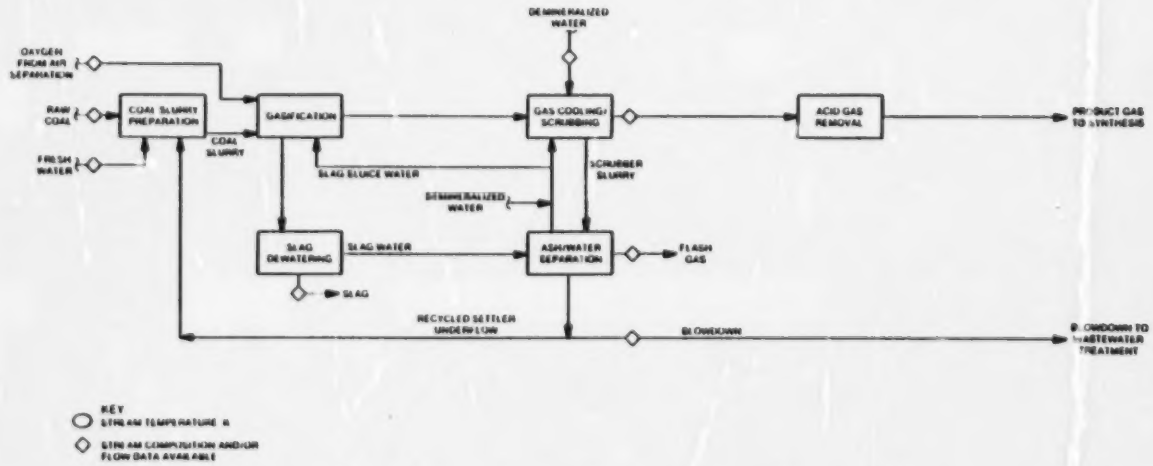


Figure 14. Simplified block flow diagram of Texaco/Ruhrchemie gasifier.

indicated. These diagrams clearly show similarities and differences among the facilities.

In general, the low-Btu gasification facilities have much less extensive downstream processing than the larger, more complex medium-Btu facilities. In addition, since the emphasis at the KRW PDU is on gasifier development, limited gas cleaning is practical. In several of the low-Btu facilities, gas cleanup consists only of removing entrained particulates, typically by the use of cyclone separators. This is particularly true of the facilities which produce a hot fuel gas for direct combustion in a process furnace. The Foster-Wheeler/STOIC facility (which features two-stage gasification) utilizes an electrostatic precipitator (ESP) to remove oil and tar particulates from the top gas and a cyclone to remove dust from the bottom gas. Of the low-Btu gasifiers tested, only the Chapman facility utilizes wet scrubbing and produces a cooled fuel gas, by-product tars and oils, and a process condensate (wastewater) stream. Some type of wet scrubbing is used in all of the medium-Btu facilities. None of the low-Btu facilities have acid gas removal systems; all of the commercial medium-Btu facilities have such units.

Ash/slag removal techniques also vary. All of the facilities except the KRW PDU use water to quench the hot ash/slag or to facilitate its removal from the gasifier vessel by sluicing. The pressurized gasifiers (Lurgi, KRW, and Texaco) all utilize lock hoppers to remove ash/slag. The others utilize ash plows, mechanical conveyors, or slide valves.

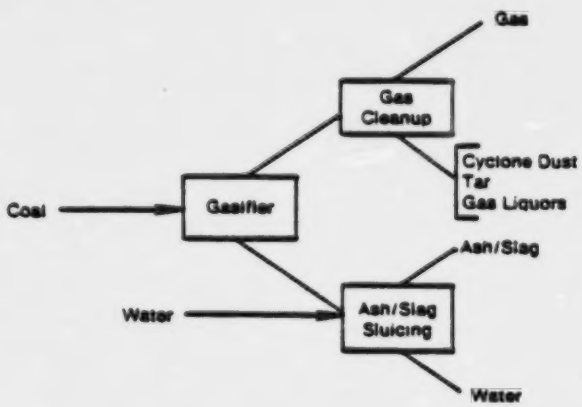
The downstream processing operations can significantly influence the fates of the various solid, liquid, and gaseous pollutants generated in the gasifier. Components originally found in the raw gas may be removed by these operations and distributed into a number of secondary solid, liquid, or gaseous streams. This distribution depends on the way in which these processes are linked together, how they are designed and operated, and on stream compositions.

Flow rate data for the major streams entering and leaving the downstream processing units for each of the facilities considered are summarized in Appendix D.

SECTION 4

RESULTS AND DISCUSSION

Trace elements are introduced to the gasification process in the coal. In the gasifier the volatile constituents from the coal and finer particles of char and ash exit in the direction of gas flow. The non-volatile constituents remain in the ash or slag and exit at the bottom of the gasifier or in the overhead particles. Trace elements in the coal will partition between the exit gas and ash depending on their volatility or their association with constituents in the coal and gases. The figure below displays the general routes for trace elements in the gasification system.



The bottom ash or slag is typically quenched or transported in water. Trace elements will partition between the solid ash or slag and the sluice water. The raw gas stream exiting the gasifier undergoes cleanup. If nothing else, particles entrained in the gas are removed by mechanical means, such as a cyclone. Additional gas cleanup may occur to remove condensible organics, water, acid gases, or specific compounds like phenols. This cleanup will

result in by-product or discharge streams with levels of trace elements dependent upon the partitioning between the gas phase and the particular cleanup stream.

The purpose of this section is to summarize the partitioning of trace elements between the various streams just described. The summary is based on data obtained from source testing at several coal gasification facilities. In some cases, enough data were obtained to close the material balance on all discharge streams and by-products. This entails having trace element concentration and flow data on the product gas, major cleanup streams (typically cyclone dust), solid ash, and ash sluice water. However, in most of the source tests the product gas trace element data were not available. In these cases, the trace element distributions in the discharge and by-product streams are expressed as a percent of the total trace element input in the coal. This is the same as assuming that the total trace element flow from discharge streams is equal to the total input (coal) trace element flow. This assumption is not entirely accurate due to large imprecisions in flow and concentration measurements. However, in most cases the results are adequate to identify general trends of trace elements in the gasification processes.

The following subsection describes the limitations in the trace element measurements and describes general aspects of quality control used in source testing.

QUALITY CONTROL

Trace element flow data summarized in this report were calculated from concentration and flow measurements made at different facilities over a several year period. The quality of the data, therefore, is influenced not only by the inherent precision and accuracy of the measurement techniques, but also by the biases resulting from the use of different instruments by different analysts. During the course of the testing, quality control (QC) requirements evolved such that no single set characterizes all of the data. However, the general QC procedures described below apply to these data.

The internal QC procedures used may be divided into two overlapping categories. One category included those procedures which were used to control data quality within the prescribed limits of acceptability. These acceptability limits were usually related to data precision, accuracy, and completeness. The other category included those procedures designed to provide a quantitative assessment of data quality, again in terms of precision, accuracy, and completeness. Some internal QC procedures, by their nature, fell in both categories.

Those procedures which served both control and assessment functions included:

- Replicate and repeat analyses (split samples),
- Blank analyses,
- Replicate samples,
- Control samples,
- Drift checks
- Spiked samples, and
- QA audits.

Procedures of this type were performed at a specified frequency, with a requirement that specific acceptance criteria be met prior to proceeding with sample analyses. Failure to meet prescribed acceptance criteria indicated the need for corrective action. By selecting appropriate acceptance criteria for QC results, the quality of the measurement data was effectively controlled within predetermined limits.

In addition to the QC checks described above, which provided both ongoing assessment and control of the measurement system, other QC procedures were

used in what is, practically speaking, strictly an assessment function. Any control benefits of these types of QC procedures are realized only over the long term as refinements of procedures and techniques. Examples of these evaluative procedures included:

- Collaborative tests,
- Methods validation studies,
- Interlaboratory (round-robin) analyses,
- Analysis of variance studies, and
- Method comparisons.

These types of QC procedures were not included in the day-to-day QC system, but rather were used for specific applications in the laboratories involved in the analyses.

The QC procedures described above were oriented to quantitative data QC in the sense that there was an obvious and direct link between each procedure and some measurable aspect of data quality. Another type of QC procedure served a control function which was more qualitative than quantitative. Examples of this type of QC procedure included:

- Training of personnel,
- Preventive maintenance,
- Documentation,
- Calibration/standardization procedures,
- Data review and calculation checks,

- Use of formatted data forms which serve as checklists,
- Careful consideration in experimental design,
- Data reduction procedures, and
- Statistical data evaluation.

In the remainder of this section, trace element behavior will be described according to the three general areas within the gasification process:

- Trace elements distributed in the gasifier between overhead (gas) and bottom (gasifier ash or slag) streams,
- Trace elements distributed to water streams, including water associated with gasifier ash and cyclone dust, and
- Trace elements distributed to gas cleanup, where trace elements are distributed between the gas and aerosols, scrubber liquor, raw gas liquor, or other liquid and solid cleanups.

GASIFICATION

Data from the following tests of gasification processes were evaluated for trace element behavior in the gasifier:

- Chapman (1),
- Wellman-Galusha (Glen-Gery) (2),
- Wellman-Galusha (Ft. Snelling) (3),

- Riley (4),
- Foster Wheeler/STOIC (5),
- Lurgi-type (Kosovo) (7)
- Texaco (8),
- KRW (9),
- Synthane (10), and
- Lurgi-type (SASOL) (11).

The Synthane coal gasification process utilizes a fluidized-bed reactor and O_2-stream gasification to produce a substitute natural gas. The trace element data for the Synthane process were obtained from the Process Development Unit (PDU) operated by the U.S. Department of Energy's Pittsburgh Energy Technology Center (9). Trace element behavior in the Koppers-Totzek (Ptolemais) gasifier could not be evaluated because adequate flow and concentration data were not publicly available (6). The remaining tests had trace element mass flow[4] data on at least the coal input and the ash discharge stream.

A convenient way to illustrate the trace element behavior in the gasifier is to present the distribution of an element's mass flow between the overhead gas and the bottom ash or slag. Non-volatile elements, or elements that do

---

[4]Mass flow is defined as:
Concentration in stream (g/kg) x Stream flow (kg/sec) = Mass flow (g/sec).
The mass flow of an element entering with the coal should equal the sum of the mass flows of the element in all discharge streams. In practice, the two are often not equal because of imprecisions or inaccuracies in measurements or poor recoveries in sampling.

not react to form volatile compounds, remain with the mineral fraction of the coal and are discharged primarily with the bottom ash. Volatile elements and elements that react to form volatile compounds are found at higher levels in the overhead stream consisting of product gas and entrained particulate matter. Where product gas measurements were not made, a low distribution of an element to the gasifier bottom ash can be assumed to indicate a high distribution in the overhead.

All of the gasification test data considered had trace element mass flow data for at least the coal and the bottom ash. Table 2 presents the percentages of each trace element measured in ash from the ten facilities. The values presented are the element mass flow in the ash as a percent of its mass flow in the inlet coal. In many cases the percent mass flow of an element in the ash exceeds 100 percent of the coal input. This is an indication of the poor precision or accuracy of some of these trace element measurements or associated flow rate data. Some general trends are apparent in evaluating the data in Table 2:

- The following elements consistently had more than 70 to 80 percent of their input mass flow in the bottom ash:

Aluminum	Cobalt	Tungsten
Barium	Potassium	Zirconium
	Uranium	

- The following elements had a large fraction of their mass flow in the overhead stream from the gasifier. They consistently had less than 70 - 80 percent of their mass flow in the ash:

Antimony	Chlorine	Mercury
Arsenic	Germanium	Selenium
Bromine	Iodine	Sulfur
Cadmium	Lead	Thallium

TABLE 2. TRACE ELEMENT DISTRIBUTION IN GASIFIER ASH EXPRESSED AS PERCENT OF INPUT

Element	Chapman	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ SIOIC	Kosovo Lurgi-Type	Sasol Lurgi-Type	Synthane Gasifier Char	Texaco (R/R) Slag	KRW Subbituminous	KRW Bituminous	KRW Lignite
Al	181.8	NA[a]	86.1	85.0	77.1	NA	65	98.5	75.3	63.0	65.2	29.9
Sb	NA	5.7	55.6	> 12.6	< 13.0	NA	33	94.6	30.0	33.9	7.1	23.0
As	< 1.4	5.7	39.0	24.7	173.5	21.3	48	88.5	60.4	35.5	28.3	26.5
Ba	108.3	NA	35.3	96.3	92.3	NA	2	99.0	84.2	20.0	17.4	3.3
Be	< 700.0	31.8	188.8	115.0	38.3	42.5	15	44.2	82.4	< 0.8	NA	< 192.1
Bi	NA	560.6	NA	NA	NA	NA	NA	61.8	> 90.5	NA	NA	NA
B	118.2	30.7	16.0	32.8	352.9	NA	NA	81.2	56.4	36.3	19.8	9.2
Br	< 1.8	18.2	16.4	16.9	18.5	NA	NA	79.0	60.4	NA	NA	NA
Cd	< 75.0	13.8	15.4	< 0.8	66.7	296.9	10	95.2	15.2	23.7	< 304.4	< 735.6
Ca	< 3000	NA	31.2	90.0	188.9	NA	26	98.9	71.1	33.5	36.1	18.9
Ce	NA	154.2	117.1	102.9	116.7	NA	NA	96.8	469.4	NA	NA	NA
Cs	ND[b]	95.4	75.5	75.0	345.7	NA	NA	96.3	362.1	NA	NA	NA
Cl	ND	41.0	35.9	36.2	4.8	NA	NA	80.4	35.7	.0	.0	.0
Cr	7.1	81.5	86.1	61.5	107.1	35.0	84	93.8	103.4	48.6	14.8	26.2
Co	150.0	71.2	NA	76.5	97.7	85.2	> 100	96.4	96.3	< 41.7	< 44.2	< 300.6
Cu	446.7	74.5	84.2	61.1	84.6	15.9	26	NA	89.1	32.5	40.1	28.8
Dy	< 0.3	56.4	< 591.8	> 115.4	NA	NA	NA	96.8	301.8	NA	NA	NA
Er	< 0.7	47.8	< 248.2	> 40.0	NA	NA	NA	98.1	120.7	NA	NA	NA
Eu	< 1.0	47.7	127.7	> 37.5	NA	NA	NA	97.9	603.6	NA	NA	NA
F	ND	12.3	7.4	26.7	205.3	NA	NA	NA	114.8	NA	NA	NA
Gd	300.0	62.1	85.6	55.6	NA	NA	NA	98.7	402.4	NA	NA	NA
Ga	< 0.1	25.0	3.7	> 8.5	57.1	NA	NA	97.0	112.1	NA	NA	NA
Ge	< 1.0	19.1	11.8	2.3E10	46.3	NA	NA	90.5	60.4	NA	NA	NA
Au	ND	NA	NA	> 11.5	NA	NA	NA	NA	NA	NA	NA	NA
Hf	NA	NA	> 84.2	NA	NA	NA	NA	98.1	301.8	NA	NA	NA
Ho	< 0.6	62.1	< 342.4	> 57.7	NA	NA	NA	98.0	226.3	NA	NA	NA
I	< 0.3	1.4	8.3	23.1	9.1	NA	NA	81.6	75.4	NA	NA	NA
Ir	NA	NA	NA	< 11.5	NA	NA	NA	NA	NA	NA	NA	NA
Fe	< 60.9	> 9.6	151.8	42.0	144.3	NA	> 100	NA	62.9	69.4	62.3	32.0
La	14.6	219.9	157.2	269.2	262.5	NA	NA	97.3	565.8	NA	NA	NA
Pb	23.6	13.9	21.2	46.2	51.9	107.7	> 100	78.1	40.0	55.3	12.5	7.5
Li	151.5	>= 50.0	81.2	34.6	68.8	NA	50	NA	377.2	14.4	43.1	32.7
Lu	NA	28.1	< 25.2	NA	NA	NA	NA	98.6	120.7	NA	NA	NA
Mg	307.7	> 9.6	24.7	80.0	210.0	NA	53	98.1	74.1	36.9	60.8	17.1
Mn	< 0.1	58.3	168.2	202.1	230.8	NA	46	94.8	82.9	30.0	9.4	115.2
Hg	NA	6.3	37.8	0.3	52.6	6.8	4	NA	200.0	NA	NA	NA
Mo	< 0.2	47.0	123.2	44.7	71.8	24.0	> 100	96.1	50.7	< 13.4	90.6	< 61.5
Nd	ND	79.5	248.2	200.0	275.0	NA	NA	97.6	492.9	NA	NA	NA
Ni	0.1	118.2	125.7	46.5	91.7	35.8	97	94.7	76.6	44.1	32.7	< 123.5
Nb	433.3	65.5	131.5	215.4	118.2	NA	NA	97.2	271.6	NA	NA	NA

[a] NA = Not analyzed.

[b] ND = Not detected.

(Continued)

TABLE 2. (Continued)

Element	Chapman	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Shell.)	Riley	Foster-Wheeler/ STOIC	Koppers	Sasol	Synthane Gasifier Char	Texaco R/R Slag	KRW Subbituminous	KRW Bituminous	KRW Lignite
Os	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pd	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P	< 4.8	> 9.6	56.3	NA	13.0	NA	NA	92.6	274.0	9.1	94.4	127.2
Pt	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
K	< 60.9	> 9.6	464.8	70.3	111.5	NA	52	59.1	75.0	23.9	64.0	15.2
Pr	< 0.1	75.0	195.0	111.1	103.7	NA	NA	98.1	NA	NA	NA	NA
Re	NA	NA	< 0.9	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rb	3.0E+4	172.3	44.8	92.3	190.9	NA	NA	94.7	335.3	NA	NA	NA
Ru	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sm	< 0.1	52.3	101.9	56.7	38.9	NA	NA	97.9	482.8	NA	NA	NA
Sc	100.0	81.9	33.5	241.2	350.0	NA	NA	95.7	277.6	NA	NA	NA
Se	36.4	9.3	121.7	NA	21.6	20.3	10	92.4	29.2	27.4	32.4	6.4
Si	< 42.7	> 9.5	73.8	NA	> 13.0	NA	81	98.7	80.8	60.3	86.7	33.5
Ag	< 0.8	31.8	5.2	> 40.7	5.0	NA	40	NA	> 83.3	ND	NA	NA
Na	< ND	9.5	21.4	78.3	108.2	NA	76	94.6	82.7	37.4	20.5	9.8
Sr	74.3	117.6	23.4	> 14.7	13.0	33.3	63	98.4	369.4	39.6	69.0	28.2
S	9.7	9.5	17.9	< 183.6	7.0	NA	NA	60.8	NA	6.3	15.6	16.7
Ta	NA	NA	67.7	NA	NA	NA	NA	NA	100.6	NA	NA	NA
Te	NA	NA	NA	NA	6.4	NA	NA	98.4	181.1	NA	NA	NA
Tb	< 3.5	54.5	83.0	> 57.7	NA	NA	NA	98.9	301.8	NA	NA	NA
Tl	NA	<= 9.4	NA	NA	NA	NA	NA	86.7	69.1	ND	ND	ND
Th	< 0.1	90.9	> 188.7	48.1	90.9	NA	NA	97.3	113.2	NA	NA	NA
Tm	NA	< 18.6	< 30.4	> 11.5	NA	NA	NA	98.5	181.1	NA	NA	NA
Sn	2000	18.6	8.4	> 55.6	16.4	NA	NA	94.2	301.8	NA	NA	NA
Ti	18.2	9.6	121.5	888.9	53.3	NA	68	98.4	94.7	46.4	86.9	53.9
W	NA	37.2	< 86.4	> 115.4	NA	NA	NA	95.9	> 905.3	NA	NA	NA
U	613.6	149.9	< 153.1	22.5	82.7	NA	NA	98.3	623.7	ND	ND	ND
V	9.5	105.2	156.4	68.0	88.5	122.7	92	97.5	82.9	26.4	52.7	48.8
Yb	NA	31.5	< 253.4	> 57.7	NA	NA	NA	99.0	20.1	NA	NA	NA
Y	< 3.6	80.0	124.1	225.0	47.4	NA	NA	98.2	352.1	NA	NA	NA
Zn	< 0.1	1.0	54.7	48.3	37.9	0.3	55	75.8	33.3	11.1	20.9	2.1
Zr	8.5	118.0	93.4	150.0	83.3	NA	NA	96.4	196.8	NA	NA	NA

[a] NA = Not analyzed.

[b] ND = Not detected.

- Several elements had inconsistent behavior or insufficient data from the tests to make general conclusions:

Boron	Iron	Silicon
Beryllium	Magnesium	Sodium
Calcium	Manganese	Strontium
Chromium	Molybdenum	Tin
Copper	Nickel	Titanium
Fluorine	Silver	Vanadium

On the average 73 percent of the ash in the coal ended up in the bottom ash, with a range of values from 46 to 100 percent. This average considers the Chapman, Wellman-Galusha, Riley, Foster-Wheeler/STOIC, Lurgi-type, and Texaco gasifiers. The remaining ash in the coal was found in the cyclone dust, product gas, or was unaccounted for. Therefore, elements with distributions in the bottom ash close to 73 percent (70 to 80 percent) are not enriched or depleted relative to the inert ash in the coal. Elements with distributions in the bottom ash less than 70 to 80 percent are volatilized relative to the coal ash.

Gasifier Overhead Stream

Some of the gasification source testing programs included measurements of trace elements in the product gas. Four of these gasifiers were all fixed-bed processes that operate at atmospheric pressure:

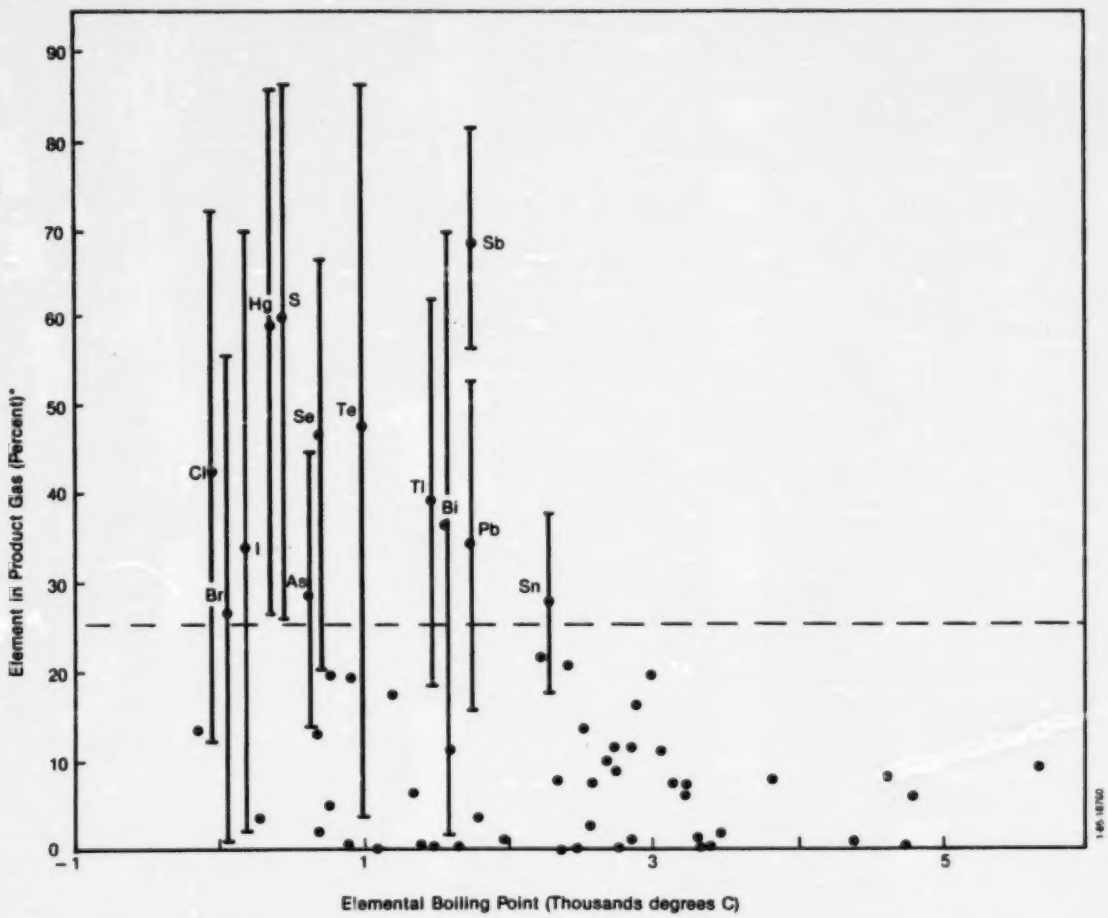
- Wellman-Galusha (Glen-Gery, 2),
- Wellman-Galusha (Ft. Snelling, 3),

- Riley (4), and
- Foster Wheeler/STOIC (5).

Figure 15 relates the portion of the elements in the product gas to elemental boiling point for these fixed bed gasifiers. Distribution in this plot is presented by the percent of the element in the gas stream including gaseous species, aerosols, and particulate matter. There is a general correlation between percent in the gas phase and boiling point, as evidenced by the plot. Excursions from the general trend may be the result of the formation of compounds more reactive than the simple elemental state (e.g., $SbCl_5$). Other anomolous behaviors may be due to elements with extreme vapor pressures at gasifier temperatures (e.g., mercury).

Elemental behavior in the four gasifier processes was remarkably similar even though widely varied coal feedstocks were used. During the Wellman-Galusha (Ft. Snelling) and Riley gasifier tests, Indian Head North Dakota lignite was the feedstock. Anthracite was the feedstock during the Wellman-Galusha (Glen-Gery) test, and bituminous coal from Colorado was the feedstock at the Foster-Wheeler/STOIC gasifier.

The Foster-Wheeler gasifier is a two stage system, with bottom and top gas streams, but no significant trends in trace element behavior were noted in the Foster-Wheeler gasifier that could be attributed to its unique design. A trend in the elemental distribution data is noted with the Riley trace element behavior. Several elements are more volatile in the Riley gasifier than in the other three processes. The elements that are more highly volatilized in the Riley process are boron, bromine, chlorine, fluorine, iodine, sodium, and mercury. The sampling and analysis errors in the Riley test were no greater or no less than in the other tests. Neither does this behavior appear to be an effect of the feedstock, since both Riley and Wellman-Galusha Ft. Snelling used North Dakota lignite. The only process difference that might account for the higher volatility of some elements at Riley is the much higher coal feed



*Includes trace elements in vapor, aerosols, and particulate matter not captured by cyclones.
Average and standard deviation from measurements made at four fixed-bed, atmospheric gasifiers.

Figure 15. Average elemental distribution of elements in product gas from fixed-bed gasifiers.

rate at the Riley gasifier than at the other gasifiers. Although temperature differences in the gasifier are another potential reason for the differences in volatility for elements, no temperature data were recorded during the test burns for the two facilities.

Theory

Four factors can be expected to influence the behavior of an element in a coal gasifier:

- The reactivity of the species,
- The boiling point or sublimation point of the species,
- The manner in which the species is incorporated in the coal matrix, and
- The temperature, and time to which the element is exposed to that temperature, in the system.

The reactivity of an element will depend upon its speciation in the coal feedstock and the environment to which it is exposed in the gasifier. A discussion of element behavior in coal gasifiers is contained in a report by IGT (Institute of Gas Technology, 22). In this report the authors evaluated the reactivity of an element based on free energies of formation of the species expected to be present in the coal and within the environment of a coal gasifier. Coal fed to a gasifier is exposed to a reducing environment with H_2, CO, CO_2, and H_2O being the major constituents of the gas. Minor constituents include H_2S, HCl, and NH_3. This reducing environment leads to the formation of reduced forms of the inorganic species in the coal. For example, arsenic is commonly found in coals as arsenopyrite, FeAsS. At elevated temperatures and in a reducing environment, the arsenopyrite is thermodynamically unstable with respect to pyrrhotite and elemental arsenic:

$$\underset{\text{arsenopyrite}}{FeAsS} \xrightarrow[CH4]{\Delta\ CO,\ H_2} \underset{\text{pyrrhotite}}{FeS} + \underset{\text{arsenic}}{As} \qquad (1)$$

The elemental arsenic thus formed sublimes at a temperature of approximately 613°C. In a reducing atmosphere containing hydrogen gas the thermodynamically stable form of arsenic is arsine gas, AsH_3;

$$\underset{\text{arsenic}}{As} \xrightarrow{\Delta\ H_2} \underset{\text{arsine gas}}{AsH_3} \qquad (2)$$

Therefore, one would expect arsenic in coal to be very volatile in a gasifier, where temperatures typically exceed 613°C.

A similar approach to estimating trace element distributions was presented by Wilde and Holbrook in a communication preceding the IGT report (23). This paper also proposed a method for estimating trace element speciation and volatility by minimization of free energies. Some of the possible trace element species present during coal gasification and their boiling or sublimation temperatures are given in Table 3. These trace element species were selected from the IGT and Wilde papers. Boiling and sublimation temperatures were obtained from the Handbook of Chemistry and Physics (24).

Although the volatilization of arsenic and several other elements is thermodynamically favorable, the kinetics of the reaction may be slow. Conversely, the boiling point of the elemental form of certain elements may indicate that they will be non-volatile. Yet, the elements may not be present in the elemental form or may react to form more volatile compounds. For example, antimony (Sb) has a high elemental boiling point, 1750°C, yet behaves as a volatile element in a gasifier. This is probably due to the formation of a compound(s) with lower boiling point(s) (e.g., antimony pentachloride, $SbCl_5$).

TABLE 3. BOILING POINTS FOR POSSIBLE INORGANIC SPECIES DURING COAL GASIFICATION[a]

Element[b]	Species Boiling Points		
	<800°C	800–1000°C	>1000°C
Al	Al		Al_2O_3
Sb	$SbCl_5$		Sb, Sb_2O_3
As	As, As_2S_3, AsH_3		
Ba			$BaCO_3$, $BaCl_2$, BaO
Be			Be, BeO
Bi	$BiCl_3$, BiO		Bi
Br	Br_2, BrCl		
Cl	Cl_2		
Cd	Cd		CdS
Cr	$Cr(CO)_6$		Cr_2O_3, $CrCl_3$
Co			Co, CoO, CoS
Cu			Cu, CuO
Ge	GeS		Ge, GeO
I	I_2		
Pb		$PbCl_2$, PbO	Pb, PbS
Hg	Hg, HgO		
Mo	H_2MoO_4, $MoCl_2$, $Mo(CO)_6$, MoS		Mo, MoO_3
Se	Se, H_2Se, SeO_2, SeO_3		
Ag	Ag_2O	Ag_2S	Ag
Te	$TeCl_2$	Te	
Tl	Tl_2CO_3, TlCl		Tl
Sn	$SnCl_2$, $SnCl_4$		Sn, SnO_2
Zn	$ZnCl_2$	Zn	ZnS

[a]Source: 23, 24.

[b]Only a few elements are listed as examples. The more volatile elements are listed where data were available.

Environmental Concerns -- Solids

The majority of the trace elements in the coal remain in the bottom ash or slag during gasification. Therefore, the first environmental concern is the potential for trace elements to enter the environment from these solid waste streams.

The criterion used for identifying environmental concerns for the solid waste discharges from gasifiers is the RCRA EP Toxicity Test. This criterion establishes whether a solid waste should be handled as environmentally hazardous or nonhazardous based on the concentration of select elements in the leachate from the waste. For the EP test, an extract is generated from a mild acetic acid (pH = 5) leaching of the solid over a 24 hour period. The concentrations of elements in the extract are compared to drinking water standards. If any leachate concentration exceeds 100 times the drinking water standard, the waste is classified EP Toxic and hazardous. The factor of 100 is an estimate of the dilution to the leachate expected from processes acting on the leachate as it migrates away from the disposal site toward a receptor.

Table 4 presents results from EP Toxicity tests performed on gasifier ash/slag solids from several different gasification systems. The solids are nonhazardous by the EP Toxicity criteria.

ASH WATER

The ash water is a discharge stream of potential environmental concern. Elemental distributions between the gasifier ash and ash water are highly varied depending on the ash handling systems.

Three of the gasification systems studied in the source test and evaluation program had data on the elemental distributions in ash water --

TABLE 4. CONCENTRATIONS OF TRACE ELEMENTS IN EP EXTRACTS OF GASIFIER ASH

	n[a]	Range, mg/L	Median, mg/L	Maximum Permissible Concentration[b]
Arsenic	7	<.003-.033	<.003	5.0
Barium	7	.074-3	.7	100.0
Cadmium	6	<.005-.10	.003	1.0
Chromium	7	<.001-.3	.003	5.0
Lead	7	<.002-.008	<.002	5.0
Mercury	6	<.005-<.002	<.0002	0.20
Selenium	6	<.003-.006	<.004	1.0
Silver	6	<.0005-.007	.003	5.0

Source: 4,5,7,8,9

[a] n = Number of samples tested.
[b] RCRA EP Toxicity Test.

- Wellman-Galusha (Ft. Snelling) (3),
- Riley (4), and
- Foster-Wheeler/STOIC (5).

Table 5 compares the concentrations of trace elements in the ash and cyclone dust waters to water quality standards. Under the normal procedures of the national pollutant discharge system these water quality critiera will not be directly compared to the concentration levels in liquid discharge streams. Some consideration for dilution or the targeted use of the receptor stream or aquifer will probably be made prior to establishing pollutant discharge limits. But the criteria serve to point out potential environmental concerns for the ash waters. Trace elements which exceed the strictest criteria at one or more of the plants included barium, boron, chromium, iron, mercury, manganese, and molybdenum.

Table 6 presents average elemental distributions in the ash waters for these plants. The distributions are the mass flow of an element in the ash water over the total mass flow in all discharge streams. Whenever possible in this report, distributions are expressed as a percentage of the sum of the mass outflow.

Most of the elements are distributed to the ash waters at levels of less than 1 percent of the total mass flow. Elements with relatively elevated distributions, such as chlorine, molybdenum, and sodium, are very water soluble elements. Several other elements showed elevated distribution in the Riley ash water but not in the Foster-Wheeler/STOIC or Wellman-Galusha ash waters. This is due to much greater flows of ash sluice water relative to coal feed rate at the Riley plant over flows at the Foster-Wheeler/STOIC and Wellman-Galusha plants. Ash water flow at Riley was 2.2 liters/sec compared to 0.007 liters/sec at the other two plants. Coal feed rates at the three plants were similar. The concentrations of trace elements in the ash waters at the three facilities were also similar (see Table 5), but the high flow of

TABLE 5. COMPARISON OF ASH AND CYCLONE DUST WATERS TO DRINKING WATER STANDARDS[a]

Element	Water Quality Limit[b]	Standard	Wellman-Galusha Ash Water (3)	Wellman-Galusha Dust Water (3)	Riley Ash Water (4)	Foster-Wheeler/ STOIC Ash Water (5)
Barium	1.0	PDW[c]	0.13	0.57	0.17	1.5
Boron	0.75	I[d]	4.6	0.99	2.6	4.4
Chromium	0.05	PDW[c]	0.007	<0.005	<0.001	0.05
Iron	0.3	SDW[e]	1.2	4.9	1.9	<0.008
Mercury	0.002	PDW[c]	NA	NA	<0.0005	0.004
Manganese	0.05	SDW[e]	0.002	<0.001	0.058	0.008
Molybdenum	0.01	I[d]	0.31	<0.04	0.19	0.12
Other Parameters						
pH (units)			9.3	10.	10.8	12.3
TDS			4300	390	2250	1700
SO_4			2860	55	1260	56
NH_4			5.4	0.97	<30	<.5
TOC			16	185	11	3.2

[a]Units are mg/L except where noted.

[b]The water quality criteria selected were the strictest criteria. These criteria would probably not be used to regulate the disposition of these effluent streams. They were used here to identify potential health problems in discharge streams.

[c]National Interim Primary Drinking Water Standards (FR 8/29/80).

[d]Long term irrigation limits for water used continuously on all soils.

[e]National Secondary Drinking Water Regulation (FR 7/29/79).

TABLE 6. ELEMENTAL DISTRIBUTIONS IN ASH WATERS

Element[a]	Percent of element in ash water[b]		
	Foster-Wheeler STOIC (5)	Riley (4)	Wellman-Galusha (3) (Ft. Snelling)
Al	0	.2	<.1
As	NA	.7	<.1
B	.2	36	<.6
Br	.6	5.8	.2
Ca	.3	2.6	.1
Cl	.8	11	10.8
Co	0	<.9	<.1
Cu	0	.4	<.1
F	0	8.3	<.1
Ga	0	3.2	<.1
I	.5	2.4	
Li	.1	<.9	.2
Mg	0	.2	<.1
Mn	0	.7	<.1
Hg	2.8	<4.	<.1
Mo	.2	18	.4
Ni	0	<.4	<.1
P	NA	1.0	<.1
K	0	19	.3
Rb	0	17	
Se	<.1	<4.	<.1
Ag	NA	>6	<.1
Na	.1	39	2.2
Sr	>.3	>13	<.1
S	.1	.3	.6
Te	.5	<.8	NA
Tl	NA	<3	NA
Sn	NA	<.8	29
W	NA	9.8	.5

[a]The following elements had distributions of less than 0.2% in the ash water: Sb, Ba, Cd, Cr, Fe, Pb, Ti, U, V and Zn.

[b]$\text{Percent in ash water} = \frac{\text{mass flow in ash water}}{\text{sum of mass flows in all stream discharges}} \times 100$

water at the Riley plant resulted in higher mass flows of elements discharged with the ash water.

Other wastewater streams may be generated at a coal gasification facility, for example, blowdown from quenching the raw product gas. At the KRW PDU, the wastewater blowdown from gas quenching contained dissolved trace elements and elevated levels of cyanide and ammonia. Table 7 presents partial analytical results for the KRW PDU wastewater during three coal tests. Elements such as boron, barium, iron and manganese were detected in the blowdown during each test. Although arsenic was detected for each test, other elements with potential volatility (beryllium, cadmium, lead, antimony, and thallium) were not observed.

GAS CLEANUP

Most of the gasification processes evaluated in the literature include some form of product gas cleanup system. If nothing else, particulate matter entrained in the gas is removed by mechanical means (e.g., cyclone).

As the gases exit the gasifier, semi-volatile trace elements may condense or adsorb onto the surfaces of particulate matter entrained in the gases. This has been postulated as a mechanism by which trace element concentrations are enriched in fly ash during conventional coal combustion (24). If condensation or adsorption occurs, then that element will be enriched in the cyclone dust. This enrichment can be expressed as an enrichment factor;

$$\text{EF (enrichment factor)} = \frac{\text{Microgram of element/total gram of stream}}{\text{Microgram of element/total gram of coal}} \times \frac{\text{\% ash in coal}}{\text{\% ash in stream}} \quad (3)$$

The right hand side of equation (3) normalizes the enrichment to the ash distribution to account for the enrichment which occurs solely from the loss of volatile organic matter from the coal. The enrichment factor will be 1.0

TABLE 7. COMPARISON OF WASTEWATER BLOWDOWN TO DRINKING WATER STANDARDS[a]

Element	Water Quality Limit[b]	Standard	KRW PDU		
			Subbituminous Coal Test	Bituminous Coal Test	Lignite Coal Test
Arsenic	0.05	PDW[c]	0.073	0.30	0.42
Boron	0.75	I[d]	6.8	10	150
Barium	1.0	PDW[c]	1.2	0.55	0.47
Chromium	0.05	PDW[c]	<0.001	<0.001	<0.001
Iron	0.3	SDW[e]	1.8	0.6	2.3
Mercury	0.002	PDW[c]	<0.03	NA[f]	<0.03
Manganese	0.05	SDW[e]	0.002	0.61	<0.001
Molybdenum	0.01	I[d]	0.003	<0.002	<0.002
Other Parameters					
pH (units)			8.4	8.4	8.7
TDS			300	220	2200
SO_4			160	330	180
NH_4			1700	1000	4100
F			1.8	20	1.7
CN			33	45	74
TOC			47	54	110

[a] Units are mg/L except where noted.
[b] The water quality criteria selected were the strictest criteria. These criteria would probably not be used to regulate the disposition of this effluent. They were used here to identify potential health problems in the effluent.
[c] National Interim Primary Drinking Water Standards (FR 8/29/80).
[d] Long term irrigation limits for water used continuously on all soils.
[e] National Secondary Drinking Water Regulations (FR 7/29/79).
[f] NA = Not analyzed.

if an element partitions between streams without enrichment or depletion, similar to the behavior of the bulk non-volatile mineral matter or ash. An enrichment factor of less than unity signifies depletion, and a factor greater than unity implies enrichment of that element.

Cyclones were used to remove particles from the gas streams at four gasifiers evaluated under the EPA source test and evaluation program: Wellman-Galusha (Glen-Gery) (2), Wellman-Galusha (Fort Snelling) (3), Riley (4), and Foster-Wheeler/STOIC (5). Cyclone dust from the Synthane PDU (10) and gas particulate matter from the KRW PDU (9) were also characterized for trace element content. The enrichment factors for elements measured in the cyclone dust are presented in Table 8. The following trace elements were highly enriched (relative to the coal ash) in the majority of cyclone dust and gas particulate samples:

Antimony	Germanium
Arsenic	Lead
Bismuth	Mercury
Cadmium	Tin
Gallium	

Additionally, thallium and zinc were enriched in the cyclone dust from the four fixed-bed gasifiers, and nickel was enriched in the gas particulate matter from KRW.

Some processes have additional gas cleanup to remove aerosols or vapor phase species from the product gas. This is especially true of the larger gasification plants, where the final gas is a pipeline product and several by-products are produced from gas extraction or cleanup. Figure 16 presents enrichment factors of several trace elements for solid discharges and by-product streams at a Lurgi-type gasifier (7). Enrichment generally increases from left to right in the figure which is also the sequence of outlet streams successively downstream from the gasifier.

TABLE 8. CYCLONE DUST ENRICHMENT FACTORS

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	Synthane	KRW Raw Product Gas Particulates		
						Subbituminous	Bituminous	Lignite
Al	NA[a]	0.8	1.2	0.7	1.0	1.9	1.0	0.7
Sb	31.4	< 3.9	0.4	33.9	5.7	8.4	3.9	0.5
As	8.1	5.7	0.8	6.1	6.2	1.3	1.4	0.6
Ba	NA	0.6	1.2	0.3	1.1	2.4	1.1	0.1
Be	1.3	0.6	0.3	1.0	2.4	1.9	1.5	4.3
Bi	4.7	> 1.8	> 0.4	7.1	NA	NA	NA	NA
B	0.6	2.6	0.6	1.4	NA	0.8	0.2	0.2
Br	1.7	5.3	0.6	1.3	11.0	NA	NA	NA
Cd	3.2	2.9	ND[b]	1.1	6.5	4.6	6.8	16.3
Ca	NA	1.3	0.9	1.3	NA	2.3	0.4	0.4
Ce	4.3	1.1	1.6	0.9	NA	NA	NA	NA
Cs	7.1	0.5	NA	0.8	NA	NA	NA	NA
Cl	2.6	1.0	0.9	1.1	NA	.0	.0	.0
Cr	1.2	0.6	4.0	1.4	1.6	3.7	7.0	0.6
Co	1.6	1.5	1.1	1.0	4.1	1.5	1.0	6.7
Cu	1.3	2.2	1.2	1.6	9.3	2.4	0.7	0.6
Dy	1.9	> 3.5	> 8.1	7.1	NA	NA	NA	NA
Er	2.1	> 1.8	> 1.6	1.4	NA	NA	NA	NA
Eu	2.4	1.2	> 1.2	1.8	NA	NA	NA	NA
F	2.5	0.8	0.9	> 51.1	NA	NA	NA	NA
Gd	1.6	0.6	> 2.4	3.6	0.8	NA	NA	NA
Ga	13.0	1.0	1.8	20.0	4.7	NA	NA	NA
Ge	10.4	5.1	> 4.0	33.9	11.0	NA	NA	NA
Au	NA	NA	0.2	NA	NA	NA	NA	NA
Hf	NA	NA	> 1.0	3.6	1.5	NA	NA	NA
Ho	1.6	> 2.4	> 2.0	1.8	NA	NA	NA	NA

(Continued)

TABLE 8. (Continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ SIOIC	Synthane	KRW Raw Product Gas Particulates		
						Subbituminous	Bituminous	Lignite
I	5.7	1.2	0.6	3.6	14.0	NA	NA	NA
Ir	NA	NA	0.2	NA	NA	NA	NA	NA
Fe	NA	1.1	0.2	1.2	0.8	1.2	0.6	0.7
La	8.8	0.8	2.4	0.8	NA	NA	NA	NA
Pb	13.6	2.4	4.5	103.6	3.8	2.7	18.9	0.2
Li	1.7	0.7	2.1	0.8	NA	0.4	1.2	0.7
Lu	1.4	NA	0.2	NA	NA	NA	NA	NA
Mg	NA	1.1	1.0	1.1	2.7	2.5	0.9	0.4
Mn	24.5	1.0	1.6	0.7	NA	1.3	1.0	2.6
Hg	315.8	> 3.5	.0	3.8	NA	NA	NA	NA
Mo	9.0	1.2	0.8	0.9	7.3	0.9	7.7	1.4
Nd	13.0	1.8	5.1	0.8	NA	NA	NA	NA
Ni	4.5	0.5	1.2	1.3	3.0	3.4	10.1	2.7
Nb	4.9	1.5	1.8	0.9	NA	NA	NA	NA
Os	NA	NA	0.2	NA	NA	NA	NA	NA
Pd	NA	NA	0.2	NA	NA	NA	NA	NA
P	> 0.7	1.2	0.5	0.4	NA	1.4	1.1	2.8
Pt	NA	NA	0.2	NA	NA	NA	NA	NA
K	NA	0.5	1.4	1.0	3.1	0.3	1.2	0.3
Pr	8.3	1.7	4.3	0.9	NA	NA	NA	NA
Re	NA	NA	0.2	NA	NA	NA	NA	NA
Rh	NA	NA	0.2	NA	NA	NA	NA	NA
Rb	0.9	0.2	6.3	0.8	6.5	NA	NA	NA
Ru	NA	NA	0.2	NA	NA	NA	NA	NA
Sm	2.6	1.2	1.3	0.7	NA	NA	NA	NA
Sc	3.3	0.6	0.5	0.4	NA	NA	NA	NA

(Continued)

TABLE 8. (Continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	Synthane	KRW Raw Product Gas Particulates		
						Subbituminous	Bituminous	Lignite
Se	3.8	8.2	0.7	2.6	NA	2.2	0.4	0.1
Si	NA	0.7	0.3	0.4	1.2	1.1	0.9	0.7
Ag	7.9	1.2	.0	0.9	NA	ND	NA	NA
Na	NA	0.9	1.0	1.4	2.0	1.5	0.5	0.2
Sr	3.3	1.2	> 0.3	0.3	1.2	2.5	2.6	0.6
S	NA	1.6	0.5	0.7	NA	0.2	0.2	0.4
Ta	NA	NA	0.2	NA	NA	NA	NA	NA
Te	≥ 2.1	> 1.2	0.2	0.9	NA	NA	NA	NA
Tb	2.8	0.6	> 4.0	1.4	NA	NA	NA	NA
Tl	≤ 34.7	> 5.3	> 2.0	21.4	NA	ND	ND	ND
Th	15.3	> 1.2	0.3	0.7	NA	NA	NA	NA
Tm	> 0.9	NA	0.2	NA	NA	NA	NA	NA
Sn	18.5	2.4	> 1.0	68.6	3.3	NA	NA	NA
Ti	NA	0.8	1.2	0.6	1.1	1.7	1.6	1.2
W	4.7	NA	4.0	7.1	NA	NA	NA	NA
U	10.7	> 0.6	0.4	0.8	NA	ND	ND	ND
V	3.9	0.5	1.3	0.9	NA	1.7	1.8	1.1
Yb	1.6	> 3.5	> 1.8	NA	NA	NA	NA	NA
Y	2.8	1.9	0.5	0.4	NA	NA	NA	NA
Zn	> 29.6	31.2	2.5	43.2	7.0	0.3	0.2	.0
Zr	1.9	1.0	1.0	0.6	NA	NA	NA	NA

[a] NA = Not analyzed.

[b] ND = Not detected.

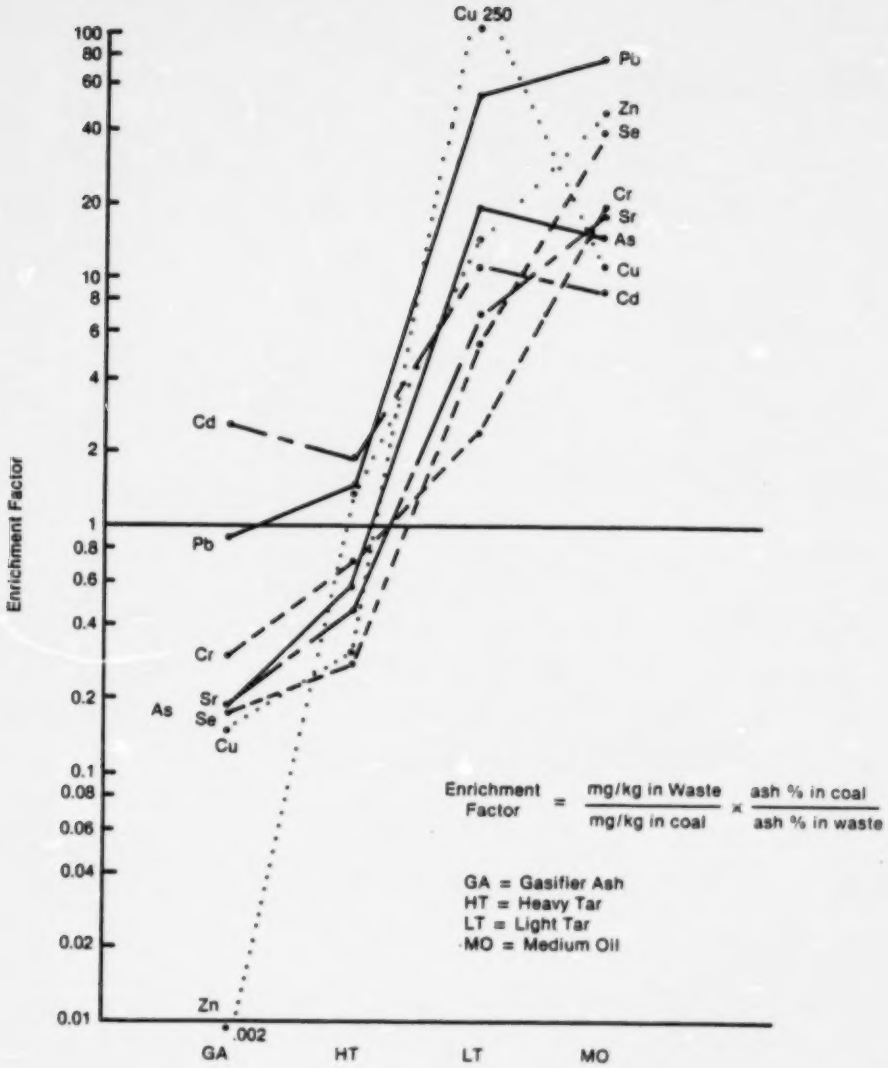


Figure 16. Enrichment factors for solid discharges and by-product streams for Lurgi-type gasifier (7).

In general, the volatile or moderately volatile elements are enriched significantly in the by-product stream. For example, the ESP oils collected from the Foster-Wheeler/STOIC (5) contained about 5 percent of the total mass output of mercury, selenium, and silver. In a test burn at the SASOL Lurgi gasifier for the Tri-State Synfuels Project (11), mercury, selenium, and silver were concentrated in the raw gas liquor or by-product streams. Other volatile and moderately volatile elements found in relatively large portions in the gas cleanup streams were arsenic, cadmium, and lead. As a final data point for distribution of trace elements into gas cleanup streams, some information was obtained from a DOE pilot demonstration unit, Synthane (10). Some of the volatile elements that partitioned to a relatively high degree to the condensate in the Synthane unit were arsenic, bromine, chlorine, and sulfur.

Environmental Concerns -- Gas Cleanup

Table 9 presents results from EP Toxicity tests performed on cyclone dust samples from two low-Btu gasifiers. Even though there is evidence of extreme enrichment of some of these elements in the cyclone dust, the leachates are non-hazardous by RCRA standards.

Other solid discharge streams resulting from gas cleanup may exist depending on the gasifier and treatment systems. These include settler fines and spent filter media from effluent treatment and tars and oils from gas cleanup. One system with settler fines, Koppers-Totzek (Ptolemais, 6), exhibited trace element concentrations in the leachate below EP Toxicity criteria. Spent filter media from a wastewater treatment system on a Lurgi gasifier were also non-toxic (Tri-State, 25).

Gaseous discharges with trace element concentrations of possible environmental concern are fugitive emissions, such as pokehole, coal hopper, and vent gases. Only a very few fugitive emissions were directly measured for trace element content, and even then only a few elements were considered (2, 7). However, gaseous fugitive emissions after the gasifier would be expected to be

TABLE 9. CONCENTRATIONS OF TRACE ELEMENTS IN EP EXTRACTS OF CYCLONE DUST

	Riley (4)	Foster-Wheeler/ STOIC (5)	Maximum Permissible Concentration[a]
Arsenic	0.004	0.12	5.0
Barium	0.39	6.9	100.0
Cadmium	<0.0005	<0.1	1.0
Chromium	<0.001	<0.2	5.0
Lead	<0.002	<0.2	5.0
Mercury	<0.0005	0.0029	0.20
Selenium	0.002	<0.004	1.0
Silver	<0.0005	<0.06	5.0

[a]RCRA Extraction Procedure (EP) Toxicity.

similar in chemical composition to the product gas, with the possible exception of different particulate loading depending on the configuration of the emission point. Table 10 presents trace element concentrations in product gases from four gasifiers. The concentrations represent combined vaporous and particulate matter values. They are compared in the table to threshold limit values (TLVs) as suggested by the American Conference of Governmental Industrial Hygienists. The TLVs refer to airborne concentrations of substances and represent conditions under which it is believed that nearly all workers may be exposed day after day without adverse effect. This direct comparison of product gas concentrations to TLVs does not give consideration to dilution by workplace air or loss, through settling, of entrained particulate matter. Elements which exceed the TLV in at least one stream include aluminum, arsenic, barium, beryllium, cadmium, copper, iron, lead, mercury, selenium, silver, and tellurium. Of these, all but arsenic, copper, lead, silver, and tellurium exceed the TLV solely due to the contribution of particulate matter.

Table 11 presents vaporous trace element concentrations in the gas phase only at the KRW PDU. Considerably fewer elements were analyzed at KRW than at the four fixed-bed gasifiers. Only nickel in the subbituminous coal test exceeded the TLV.

TABLE 10. COMPARISON OF TRACE ELEMENT CONCENTRATIONS IN PRODUCT GASES TO TLV'S

Element	Regulated Compound	TLV[a]	Elemental concentrations, g/m^3, as determined by spectrometry: Wellman-Galusha (Glen-Gery) Combusted Product Gas, Vapor, and Aerosols (2)	Wellman-Galusha (Ft. Snalling) Product Gas, Vapor, and Particles (3)	Riley Product Gas, Vapor, and Particles (4)	Foster-Wheeler/ STOIC Product Gas and Aerosols (5)
Al	metal oxides	10,000	>130	27,000[P]	260	5,300
Sb	total	500	1	<400	21	12
As	soluble components	200	18	>390[P]	<510	16
Ba	soluble comp.	500	16	7,600[P]	>270	62
Be		2	NA	2.6[P]	NA	.16
B	borates	1,000	230	>560	610	180
Br	bromine	700	2.8	130	9.2	42
Cd	dust & soil	50	0.70	270[P]	NA	.59
Cs	hydroxide	2,000	1	2.3	<78	.14
Cl	chlorine	3,000	490	>3,200[P]	230,000[V]	430
Cr	metal	500	>680	100	180	82
Co	dust & metal	100	<7	>15	<30	.84
Cu	fume	200	5.3	280[P]	78	290[V]
F	fluorine	2,000	32	1,300	350	>190
Ge	tetrahydride	600	.35	7.2	<93	3.7
Hf		500	NA	2.9	NA	<.39
Fe	soluble salts	1,000	>590	<33,000[P]	NA	2,700[P]
Pb	inorg. dust & fumes	150	4.2	160	180[P]	170
Mn	fume	1,000	27	130	330	18
Hg	total less alkyl	50	NA	6,500[P]	12	2.4
Mo	soluble comp.	5,000	68	9.7	66	6.4
Ni	carbonyl	350	290	120	72	120
Se	total	200	12	15,000[P]	<9	<1.7
Ag	soluble comp.	10	7.4	140	<90	<.39
Te	total	100	<.1	.97	140[V]	.20
Tl	soluble comp.	100	NA	3.2	<84	2.3
Sn	metal	2,000	7.2	14	<85	15
W	soluble comp.	1,000	1.0	NA	NA	.78
U	total	200	4.4	7.8	NA	1.4
V	V_2O_5	50	3.0	37	39	4.7
Zn	$ZnCl_2$	1,000	28	510	>540	70

[a]Compounds with suggested threshold limit values (TLV) as suggested by the American Conference of Governmental Industrial Hygienists ("TLV for Chemical Substances and Physical Agents in the Work Environment", ACGIH, ISBN: 0-936712-45-7, Cincinnati, OH 1983). Values are in g/m^3.

P = Largely contributed by particulate matter.

V = Largely contributed by vapor phase.

NA = Not analyzed

TABLE 11. COMPARISON OF VAPOROUS TRACE ELEMENT CONCENTRATIONS IN PRODUCT GASES TO TLV'S

Element	Regulated Compound	TLV[a]	Vaporous elemental concentrations, ug/m^3, as determined by spectrometry — KRW PDU (9)		
			Subbituminous Coal Test	Bituminous Coal Test	Lignite Test
Al	metal oxides	10,000	<24	16	480
Sb	total	500	NA	NA	NA
As	soluble components	200	NA	NA	NA
Ba	soluble comp.	500	55	9	73
Be		2	<0.1	<0.1	<0.1
B	boratas	1,000	380	38	37
Br	bromine	700	NA	NA	NA
Cd	dust & soil	50	13	<.5	<.5
Ca	hydroxide	2,000	NA	NA	NA
Cl	chlorine	3,000	NA	NA	NA
Cr	metal	500	<0.5	<0.5	0.2
Co	dust & metal	100	<3	<1	<1
Cu	fume	200	<0.6	0.6	0.6
F	fluorine	2,000	NA	NA	NA
Ge	tetrahydride	600	NA	NA	NA
Hf		500	NA	NA	NA
Fe	soluble salts	1,000	100	11	730
Pb	inorg. dust & fumes	150	NA	NA	NA
Mn	fume	1,000	5	0.5	8.6
Hg	total less alkyl	50	27	5	9
Mo	soluble comp.	5,000	<0.8	0.4	<0.4
Ni	carbonyl	350	1,000	<0.5	0.8
Se	total	200	NA	NA	NA
Ag	soluble comp.	10	NA	NA	NA
Te	total	100	NA	NA	NA
Tl	soluble comp.	100	NA	NA	NA
Sn	metal	2,000	NA	NA	NA
W	soluble comp.	1,000	NA	NA	NA
U	total	200	NA	NA	NA
V	V_2O_5	50	<1.6	1.8	1.8
Zn	$ZnCl_2$	1,000	<1.5	2.3	5.0

[a]Compounds with suggested threshold limit values (TLV) as suggested by the American Conference of Governmental Industrial Hygienists ("TLV for Chemical Substances and Physical Agents in the Work Environment", ACGIH, ISBN: 0-936712-45-7, Cincinnati, OH 1983). Values are in g/m^3.

NA = Not analyzed

REFERENCES

1. Page, G.C. Environmental Assessment: Source Test and Evaluation Report--Chapman Low BTU Gasification. EPA-600/7-78-202; PB-289940. Radian Corp., Austin, TX, October 1978.

2. Thomas, W.C., K.N. Trede and G.C. Page. Environmental Assessment: Source Test and Evaluation Report--Wellman-Galusha (Glen Gery) Low BTU Gasification. EPA-600/7-79-185; PB80-102551. Radian Corp., Austin, TX, August 1979.

3. Kilpatrick, M., et al. Environmental Assessment: Source Test and Evaluation Report--Wellman-Galusha (Ft. Snelling) Low BTU Gasification. EPA-600/7-80-097; PB80-219330. Radian Corp., Austin, TX, May 1980.

4. Fuchs, M.R., et al. Environmental Assessment: Source Test and Evaluation Report--Riley Gas Producer. EPA-600/7-84-092; PB84-246396. Radian Corp., Austin, TX, September 1984.

5. Fuchs, M.R., et al. Environmental Assessment: Source Test and Evaluation Report--STOIC Low-Btu Gasifier. EPA-600/7-86-006; PB86-167012. Radian Corp., Austin, TX, February 1986.

6. Zee, C.A., J.F. Clausen and K.W. Crawford. Environmental Assessment: Source Test and Evaluation Report--Koppers-Totzek Process. EPA-600/7-81-009; PB81-185613. TRW, Inc. Redondo Beach, CA, January 1981.

7. Lee, K.W., et al. Environmental Assessment: Source Test and Evaluation Report--Lurgi (Kosovo) Medium BTU Gasification, Phase 1. EPA-600/7-81-142; PB82-114075. Radian Corp., Austin, TX, August 1981.

8. Wetherold, R.G., et al. Environmental Characterization of the Texaco Coal Gasification Process at Ruhrkohle/Ruhrchemie in Oberhausen-Holten, Federal Republic of Germany. EPRI AP-2811, Radian Corporation, Austin, TX, January 1983.

9. Mann, R.M., G.E. Harris, W.R. Menzies, A.V. Simonson and W.A. Williams, Environmental, Health and Safety Data Base for the KRW Coal Gasification Process Development Unit. Gas Research Institute 85/0123. Radian Corporation, Austin, TX, June 1985.

10. Koppenaal, D.W. Trace Element Studies on Coal Gasification Process Streams. Dissertation presented to University of Missouri, Columbia, MO, September 1978, NTIS report no. TID-290-22.

11. Tri-State Synfuels Co. Tri-State Synfuels Project Commercial-Scale Coal Test: Vol. 6A. Export Sample Program/Wastewater Treatability Study Summary Report. DOE/OR/20807-T1-V.6A; DE83007445. Houston, TX, November 1982.

12. Brown, J. and A. Guest. Continuing Analysis of Trace Elements in Coal. Hydro-Electric Power Comm. of Ontario, 1973.

13. Cowherd, C., Jr., et al. Hazardous Emission Characterization of Utility Boilers. Midwest Research Institute. EPA 650/2-75-066; PB245017, July 1975.

14. Klein, D.H., et al. Pathways of Thirty-seven Trace Elements through Coal-fired Power Plant. Env. Sci. Tech., 9(10): 973, 1975.

15. Lee, R.E. Jr., et al. Concentration and Size of Trace Metal Emissions from a Power Plant, a Steel Plant and a Cotton Gin. Env. Sci. Tech., 9(7): 643, 1975.

16. Davison, R.L., et al. Trace Elements in Fly Ash. Dependence of Concentration on Particle Size. Env. Sci. Tech., 8(13): 1107, 1974.

17. Goldbery, A.J. A Survey of Emissions and Controls for Hazardous and Other Pollutants. EPA-R4-73-021; PB223568, Washington, D.C., February 1973.

18. Fisher, G.L., et al. Size-Dependence of the Physical and Chemical Properties of Coal Fly Ash. ACS Div. of Fuel Chem, Prepr. 22(4), 1977.

19. Billings, C.E., et al. Mercury Balance on a Large Pulverized Coal-Fired Furnance. J. APCA, 23(9): 773, 1973.

20. Billings, C.E. and R.W. Matson. Mercury Emissions from Coal Combustion. Sci. 176, 1232-33, 1972.

21. Kaakinen, J.W., M.E. Lawasani, and E.R. West. Trace Element Behavior in Coal-Fired Power Plants. Env. Sci. Tech. 9(9): 862, 1975.

22. Hill, A.H., G.L. Anderson and D.K. Fleming. Theoretical Investigation of Selected Trace Elements in Coal Gasification Plants. EPA-600/7-83-047; PB83-250001. Institute of Gas Technology, Chicago, IL, August 1983.

23. Wilde, K.A. and M.E. Halbrook. Thermodynamic Distribution of Trace Elements by Minimization of Free Energy. Ind. & Eng. Chem. Fundamentals, 16(4), November 1977.

24. Weast, R.C., and S.M. Selby, editors. Handbook of Chemistry & Physics, 48th ed. The Chemical Rubber Co., Cleveland, OH, 1967.

25. Davison, R.L., D.F.S. Natusch, and J.R. Wallace. Trace Elements in Fly Ash. Env. Sci. and Technology, 8(13), December 1974.

26. Wetzel, R.E., K.W. Crawford and W.C. Yee. Environmental Aspects of the GKT Coal Gasification Process. In Symposium Proceedings: Environmental Aspects of Fuel Conversion Technology - VI, EPA-600/9-82-017; PB83-128121, August 1982, pp 42 - 56.

APPENDIX A

MASS BALANCE DATA FOR COAL GASIFICATION TESTS (PERCENT OF INPUT)

These tables present the distributions of trace elements in discharge streams as percentage of input (percent of coal). Data from the following gasifiers are presented:

- Chapman,
- Wellman-Galusha (Glen-Gery),
- Wellman-Galusha (Ft. Snelling),
- Riley,
- Foster-Wheeler/STOIC,
- Lurgi-type (Kosovo),
- Lurgi (SASOL),
- Synthane,
- Texaco (Ruhrkohle/Ruhrchemie), and
- KRW.

Discharge streams included gasifier ash/slag, ash sluice water, product gas, cyclone dust, and "other" streams.

TABLE A-1. TRACE ELEMENT DISTRIBUTION IN GASIFIER ASH EXPRESSED AS PERCENT OF INPUT

Element	Chapman	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	Lurgi-type (Kosovo)	Lurgi (SASOL)	Synthane Gasifier Char	Texaco P/R Slag	KBW Subbituminous	KBW Bituminous	KBW Lignite
Al	181.8	NA[a]	86.1	85.0	77.1	NA	65	98.5	75.3	63.0	65.2	29.9
Sb	NA	5.7	53.6	> 12.6	< 13.0	NA	33	94.6	30.0	33.9	7.1	23.0
As	< 1.4	5.7	39.0	24.7	173.5	21.3	48	88.5	60.4	35.5	28.3	26.5
Ba	108.3	NA	35.3	96.3	92.3	NA	2	99.0	84.2	20.0	17.4	3.3
Be	< 700.0	31.8	188.8	115.0	38.3	42.5	15	44.2	82.4	< 0.8	NA	< 192.1
Bi	NA	560.6	NA	NA	NA	NA	NA	61.8	> 90.5	NA	NA	NA
B	118.2	30.7	16.0	32.8	352.9	NA	NA	81.2	56.4	36.3	19.8	9.2
Br	< 1.8	18.2	16.4	16.9	18.5	NA	NA	79.0	60.4	NA	NA	NA
Cd	< 75.0	13.8	15.4	< 0.8	66.7	296.9	10	95.2	15.2	23.7	< 304.4	< 735.6
Ca	< 3000	NA	31.2	90.0	188.9	NA	26	98.9	71.1	33.5	36.1	18.9
Ce	NA	154.2	117.1	102.9	116.7	NA	NA	96.8	469.4	NA	NA	NA
Cs	ND	95.4	75.5	75.0	345.7	NA	NA	96.3	362.1	NA	NA	NA
Cl	ND	41.0	35.9	36.2	4.8	NA	NA	80.4	35.7	.0	.0	.0
Cr	7.1	81.5	86.1	61.5	107.1	35.0	84	93.8	103.4	48.6	14.8	26.2
Co	150.0	71.2	NA	76.5	97.7	85.2	> 100	96.4	96.3	< 41.7	< 44.2	< 300.6
Cu	446.7	74.5	84.2	61.1	84.6	15.9	26	NA	89.1	32.5	40.1	28.8
Dy	< 0.3	56.4	< 591.8	> 115.4	NA	NA	NA	96.8	301.8	NA	NA	NA
Er	< 0.7	47.8	< 248.2	> 40.0	NA	NA	NA	98.1	120.7	NA	NA	NA
Eu	< 1.0	47.7	127.7	> 37.5	NA	NA	NA	97.9	603.6	NA	NA	NA
F	ND	12.3	7.4	26.7	205.3	NA	NA	NA	114.8	NA	NA	NA
Gd	300.0	62.1	85.6	55.6	NA	NA	NA	98.7	402.4	NA	NA	NA
Ga	< 0.1	25.0	3.7	> 8.5	57.1	NA	NA	97.0	112.1	NA	NA	NA
Ge	< 1.0	19.1	11.8	2.3810	46.3	NA	NA	90.5	60.4	NA	NA	NA
Au	ND	NA	NA	> 11.5	NA	NA	NA	NA	NA	NA	NA	NA
Hf	NA	NA	> 84.2	NA	NA	NA	NA	98.1	301.8	NA	NA	NA
Ho	< 0.6	62.1	< 342.4	> 57.7	NA	NA	NA	98.0	226.3	NA	NA	NA
I	< 0.3	1.4	8.3	23.1	9.1	NA	NA	81.6	75.4	NA	NA	NA
Ir	NA	NA	NA	< 11.5	NA	NA	NA	NA	NA	NA	NA	NA
Fe	< 60.9	> 9.6	151.8	42.0	144.3	NA	> 100	NA	62.9	69.4	62.3	32.0
La	14.6	219.9	157.2	269.2	262.5	NA	NA	97.3	565.8	NA	NA	NA
Pb	23.6	13.9	21.2	46.2	51.9	107.7	> 100	78.1	40.0	55.3	12.5	7.5
Li	151.5	>= 50.0	81.2	34.6	68.8	NA	50	NA	377.2	14.4	43.1	32.7
Lu	NA	28.1	< 25.2	NA	NA	NA	NA	98.6	120.7	NA	NA	NA
Mg	307.7	> 9.6	24.7	80.0	210.0	NA	53	98.1	74.1	36.9	60.8	17.1
Mn	< 0.1	58.3	168.2	202.1	230.8	NA	46	94.8	82.9	30.0	9.4	115.2
Hg	NA	6.3	37.8	0.3	52.6	6.8	4	NA	200.0	NA	NA	NA
Mo	< 0.2	47.0	123.2	44.7	71.8	24.0	> 100	96.1	50.7	< 13.4	90.6	< 61.5
Nd	< ND	79.5	248.2	200.0	275.0	NA	NA	97.6	492.9	NA	NA	NA
Ni	0.1	118.2	125.7	46.5	91.7	35.8	97	94.7	76.6	44.1	32.7	< 123.5
Nb	433.3	65.5	131.5	215.4	118.2	NA	NA	97.2	271.6	NA	NA	NA
Os	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pd	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P	< 4.8	> 9.6	56.3	NA	13.0	NA	NA	92.6	274.0	9.1	94.4	127.2
Pt	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
K	< 60.9	> 9.6	464.8	70.3	111.5	NA	52	59.1	75.0	23.9	64.0	15.2
Pr	< 0.1	73.0	195.0	111.1	103.7	NA	NA	98.1	NA	NA	NA	NA
Re	NA	NA	< 0.9	NA	NA	NA	NA	NA	NA	NA	NA	NA

(continued)

TABLE A-1. TRACE ELEMENT DISTRIBUTION IN GASIFIER ASH EXPRESSED AS PERCENT OF INPUT (continued)

Element	Chapman	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ SYMIC	Lurgi-type (Kosovo)	Lurgi (SASOL)	Synthane Gasifier Char	Texaco R/R Slag	KRW		
										Subbituminous	Bituminous	Lignite
Bh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nb	3.0E+4	172.3	44.8	92.3	190.9	NA	NA	94.7	335.3	NA	NA	NA
Ru	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sb	< 0.1	52.3	101.9	56.7	38.9	NA	NA	97.9	482.8	NA	NA	NA
Sc	100.0	81.9	33.5	241.2	350.0	NA	NA	95.7	277.6	NA	NA	NA
Se	36.4	9.3	121.7	NA	21.6	20.3	10	92.4	29.2	27.4	32.4	6.4
Si	< 42.7	> 9.5	73.8	NA	> 13.0	NA	81	98.7	80.8	60.3	86.7	33.5
Ag	< 0.8	31.8	5.2	> 40.7	5.0	NA	40	NA	> 83.3	ND	NA	NA
Na	ND	9.5	21.4	78.3	108.2	NA	76	94.6	82.7	37.4	20.5	9.8
Sr	74.3	117.6	23.4	> 14.7	13.0	33.3	63	98.4	369.4	39.6	69.0	28.2
S	9.7	9.5	17.9	< 183.6	7.0	NA	NA	60.8	NA	6.3	15.6	16.7
Ta	NA	NA	67.7	NA	NA	NA	NA	NA	100.6	NA	NA	NA
Te	NA	NA	NA	NA	6.4	NA	NA	98.4	181.1	NA	NA	NA
Tb	< 3.5	54.5	83.0	> 57.7	NA	NA	NA	98.9	301.8	NA	NA	NA
Tl	NA	<= 9.4	NA	NA	NA	NA	NA	86.7	69.1	ND	ND	ND
Th	< 0.1	90.9	> 188.7	48.1	90.9	NA	NA	97.3	113.2	NA	NA	NA
Ta	NA	< 18.6	< 30.4	> 11.5	NA	NA	NA	98.5	181.1	NA	NA	NA
Sn	2000	18.6	8.4	> 55.6	16.4	NA	NA	94.2	301.8	NA	NA	NA
Ti	18.2	9.6	121.5	888.9	53.3	NA	68	98.4	94.7	46.4	86.9	53.9
W	NA	37.2	< 86.4	> 115.4	NA	NA	NA	95.9	> 905.3	NA	NA	NA
U	613.6	149.9	< 153.1	22.5	82.7	NA	NA	98.3	623.7	ND	ND	ND
V	9.5	105.2	156.4	68.0	88.5	122.7	92	97.5	82.9	26.4	52.7	48.8
Yb	NA	31.5	< 253.4	> 57.7	NA	NA	NA	99.0	20.1	NA	NA	NA
Y	< 3.6	80.0	124.1	225.0	47.4	NA	NA	98.2	352.1	NA	NA	NA
Zn	< 0.1	1.0	54.7	48.3	37.9	0.3	55	75.8	33.3	11.1	20.9	2.1
Zr	8.5	118.0	93.4	150.0	83.3	NA	NA	96.4	196.8	NA	NA	NA

[a] NA = Not analyzed.
[b] ND = Not detected.

TABLE A-2. TRACE ELEMENT DISTRIBUTION IN ASH SLUICE WATER EXPRESSED AS PERCENT OF INPUT

Element	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC
Al	< 0.1	0.1	.0
Sb	< 0.4	NA[a]	ND
As	< 0.1	0.3	ND
Ba	ND[b]	0.1	.0
Be	NA	< 1.1	NA
Bi	NA	NA[a]	NA
B	< 0.1	22.8	0.6
Br	0.1	5.4	0.2
Cd	ND	< 0.1	NA
Ca	.0	2.5	0.6
Ce	< 0.1	< 0.2	NA
Cs	NA	< 4.1	ND
Cl	5.1	117.0	0.1
Cr	< 0.1	< 0.1	.0
Co	NA	< 0.8	.0
Cu	< 0.1	0.2	.0
Dy	NA	NA	NA
Er	NA	NA	NA
Eu	NA	< 1.1	NA
F	ND	4.4	.0
Gd	NA	NA	NA
Ga	ND	1.1	.0
Ge	NA	NA	NA
Au	NA	NA	NA
Hf	NA	NA	NA
Ho	NA	NA	NA
I	NA	8.5	0.1
Ir	NA	< 1.7	NA
Fe	< 0.2	.0	ND
La	< 0.2	< 0.6	NA
Pb	ND	< 0.2	.0
Li	0.2	< 0.5	0.1
Lu	NA	NA	NA
Mg	ND	0.2	.0
Mn	< 0.2	1.4	.0
Hg	< 0.1	< 0.8	2.0
Mo	0.7	11.1	0.1
Nd	NA	< 0.6	0.0
Ni	< 0.1	< 0.2	.0
Nb	< 0.1	< 0.3	.0

(Continued)

TABLE A-2. (Continued)

Element	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC
Al	< 0.1	0.1	.0
Os	NA	NA	NA
Pd	NA	NA	NA
P	< 0.1	ND	.0
Pt	NA	NA	NA
K	1.5	17.6	.0
Pr	< 0.2	< 0.8	NA
Re	NA	NA	NA
Rh	NA	NA	NA
Rb	NA	23.8	.0
Ru	NA	NA	NA
Sm	NA	< 0.3	NA
Sc	NA	< 0.6	< 0.1
Se	< 0.4	NA	ND
Si	< 0.1	NA	.0
Ag	ND	> 5.7	NA
Na	0.5	52.2	0.1
Sr	ND	> 2.4	> .0
S	0.5	NA	0.1
Ta	NA	NA	NA
Te	NA	NA	.0
Tb	NA	NA	NA
Tl	NA	NA	NA
Th	NA	< 0.4	ND
Tm	NA	NA	NA
Sn	13.1	NA	NA
Ti	< 0.1	< 0.2	.0
W	< 0.5	> 18.5	NA
U	NA	< 0.4	ND
V	< 0.2	< 0.1	.0
Yb	NA	NA	NA
Y	NA	< 0.1	.0
Zn	< 0.1	< 0.2	.0
Zr	< 0.1	< 0.2	.0

[a]NA = Not analyzed.

[b]ND = Not detected.

TABLE A-3. TRACE ELEMENT DISTRIBUTION IN CYCLONE DUST EXPRESSED AS PERCENT OF INPUT

Element	Chapman	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	Synthane Filter Fines[a]
Al	0.55	NA[b]	1.6	2.3	0.1	1.1
Sb	< 600	5.7	7.6	> 0.7	7.0	5.4
As	< 0.09	1.5	11.6	1.5	1.3	4.5
Ba	2.42	NA	1.2	2.5	.0	1.0
Be	NA	0.2	< 0.2	1.4	0.2	22.2
Bi	NA	1.1	< 3.6	> 0.6	NA	33.3
B	3.64	0.1	1.2	1.1	0.3	18.3
Br	< 0.15	0.3	10.3	0.9	0.3	6.9
Cd	< 0.07	0.6	5.3	ND[c]	0.2	4.8
Ca	< 10.91	NA	2.7	1.8	0.3	0.8
Ce	> 100	0.8	2.1	2.8	0.2	3.2
Cs	NA	1.3	0.9	6.0	0.2	3.7
Cl	NA	4.9	2.0	2.1	0.2	2.3
Cr	0.71	0.2	1.3	5.4	0.3	2.1
Co	0.91	0.3	NA	2.1	0.2	3.1
Cu	34.67	0.2	4.5	2.2	0.3	NA
Dy	< 0.03	0.3	< 7.2	> 12.3	NA	3.2
Er	< 0.06	0.4	< 3.5	> 2.5	NA	1.9
Eu	< 0.09	0.4	2.5	2.0	NA	2.1
F	0.70	0.5	1.6	1.2	> 10.5	NA
Gd	< 5.45	0.3	1.2	> 3.0	NA	1.3
Ga	< 0.01	2.3	2.1	3.7	4.0	2.6
Ge	< 0.09	1.9	9.9	> 6.2	7.0	6.6
Au	NA	NA	NA	NA	NA	NA
Hf	NA	NA	NA	> 1.5	NA	1.9
Ho	< 0.05	0.3	< 4.9	> 3.1	NA	2.0
I	< 0.03	1.1	2.4	2.8	0.7	18.4
Ir	NA	NA	NA	< 0.3	NA	NA
Fe	< 1.09	0.1	2.2	0.6	0.2	NA
La	0.22	1.8	1.6	7.4	0.2	2.7
Pb	5.45	2.4	4.8	11.5	21.0	18.6
Li	0.30	0.3	1.4	3.1	0.2	NA
Lu	NA	0.3	NA	> 0.3	NA	1.4
Mg	2.23	0.1	2.1	1.9	0.2	1.4
Mn	8.57	4.6	2.1	2.9	0.1	0.6
Hg	NA	57.6	6.8	0.1	0.8	NA
Mo	< 0.02	1.7	2.3	1.5	0.2	3.9
Nd	NA	2.4	3.5	11.8	0.2	2.4
Ni	5.45	0.8	1.0	1.9	0.3	4.0
Nb	< 0.20	0.9	3.0	3.7	0.2	2.8
Os	NA	NA	NA	NA	NA	NA

(Continued)

TABLE A-3. (Continued)

Element	Chapman	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	Synthane Filter Fines[a]
Pd	NA	NA	NA	NA	NA	NA
P	< 2.09	0.1	2.4	NA	> 0.1	0.9
Pt	NA	NA	NA	NA	NA	NA
K	< 2.09	0.1	10.6	> 0.5	0.2	2.0
Pr	< 0.01	1.5	3.4	7.4	0.2	1.9
Re	NA	NA	NA	NA	NA	NA
Rh	NA	NA	NA	NA	NA	NA
Rb	0.45	NA	0.4	9.2	0.2	5.1
Ru	NA	NA	NA	NA	NA	NA
Sm	< 0.01	0.4	2.3	2.4	0.1	2.1
Sc	0.30	3.3	1.2	2.4	1.0	3.9
Se	< 0.01	0.1	16.7	NA	0.5	1.2
Si	< 1.09	0.4	1.4	NA	> 0.1	1.3
Ag	< 0.07	0.3	2.4	NA	<= 0.2	NA
Na	NA	.0	1.8	> 2.1	0.3	0.8
Sr	NA	1.1	2.5	> 0.8	0.1	1.6
S	0.25	NA	3.1	< 10.1	0.1	1.2
Ta	NA	NA	NA	NA	NA	NA
Te	NA	NA	< 2.3	> 0.6	0.2	1.6
Tb	< 0.30	0.5	1.2	> 6.2	NA	1.1
Tl	NA	<= 6.4	< 10.4	> 3.1	NA	13.1
Th	< 0.01	2.7	> 2.3	0.4	0.1	2.7
Tm	NA	< 0.2	NA	> 0.3	NA	1.5
Sn	< 0.06	3.4	4.6	> 1.2	13.6	5.8
Ti	0.11	0.1	1.6	26.7	0.1	1.2
W	NA	0.9	< 8.6	> 6.2	NA	4.1
U	2.27	2.0	< 1.1	0.6	0.2	1.7
V	0.48	0.7	0.9	2.2	0.2	2.0
Yb	NA	0.3	< 7.0	> 2.8	NA	1.0
Y	0.17	0.6	4.0	1.4	0.1	1.8
Zn	< 0.01	0.4	63.4	4.8	8.6	6.3
Zr	0.28	0.4	2.0	3.0	0.1	3.6

[a]Calculated as percent of detected output. Does not include all streams.

[b]NA = Not analyzed.

[c]ND = Not detected.

TABLE A-4. TRACE ELEMENT DISTRIBUTION IN WASTE STREAMS EXPRESSED AS PERCENT OF INPUT

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha[a] (Ft. Shell.)	Riley Vapors	Riley Aerosols	Foster-Wheeler/ STOIC	Lurgi-type (Kosovo) Combined Flare Gas	KRW Vapors Subbituminous	KRW Vapors Bituminous	KRW Vapors Lignite	KRW Particulates Subbituminous	KRW Particulates Bituminous	KRW Particulates Lignite
Al	NA[b]	< 0.1	0.3	> .0	0.1	NA	.0	.0	.0	63.5	10.9	29.3
Sb	10.9	384.8	NA	> 29.1	20.4	NA	0.0	0.0	0.0	285.6	42.9	80.0
As	> 6.2	28.2	2.3	< 9.4	3.1	2.7E-04	0.0	0.0	0.0	43.7	15.8	43.0
Ba	NA	0.2	0.1	> 0.4	.0	NA	0.1	.0	0.1	81.6	12.1	17.1
Be	.0	NA	< 1.8	< 1.5	0.2	1.4E-03	< 0.1	0.1	< 0.1	65.9	16.0	59.0
Bi	5.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B	ND[c]	0.1	NA	1.0	2.5	NA	7.3	0.2	0.1	27.4	2.6	2.2
Br	0.1	0.9	68.5	18.5	7.4	NA	NA	NA	NA	NA	NA	NA
Cd	40.9	1.0	< 1.8	< 0.6	0.2	5.0E-04	14.0	< 0.4	< 0.3	157.6	74.1	76.6
Ca	NA	0.1	0.7	> .0	0.2	NA	0.1	.0	0.1	78.3	4.4	41.4
Ce	0.1	0.1	NA	2.4	0.2	NA	NA	NA	NA	NA	NA	NA
Cs	0.1	2.6	60.0	< 21.5	0.2	NA	NA	NA	NA	NA	NA	NA
Cl	> 19.0	2.0	> 872.3	6.9	5.5	NA	0.0	0.0	0.0	.0	.0	.0
Cr	0.2	8.0	3.8	31.2	5.6	NA	.0	.0	.0	125.3	76.4	23.9
Co	0.4	NA	< 3.0	<= 1.5	0.2	4.3E-04	< 0.2	< 0.1	< 0.2	50.1	10.7	33.0
Cu	0.5	2.5	< 0.2	4.3	21.5	1.1E-03	.0	.0	.0	80.6	8.0	34.0
Dy	1.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Er	< 0.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Eu	0.3	NA	< 18.0	< 2.0	NA	NA	NA	NA	NA	NA	NA	NA
F	0.2	1.0	18.2	2.7	9.5	NA	NA	NA	NA	NA	NA	NA
Gd	0.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ga	> 4.6	0.1	NA	5.0	3.7	NA	NA	NA	NA	NA	NA	NA
Ge	0.1	0.6	> 22.3	> 92.3	6.5	NA	NA	NA	NA	NA	NA	NA
Au	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hf	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ho	0.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	.0	7.0	NA	< 11.5	0.7	NA	NA	NA	NA	NA	NA	NA
Ir	NA	NA	< 27.7	< 2.2	NA	NA	NA	NA	NA	NA	NA	NA
Fe	.0	0.2	.0	> .0	0.3	NA	.0	0.0	.0	40.1	6.9	2.2
La	0.2	0.3	NA	8.5	0.2	NA	NA	NA	NA	NA	NA	NA
Pb	4.1	16.0	31.5	69.2	19.8	1.0E-03	0.0	0.0	0.0	90.7	206.3	12.1
Li	0.7	0.6	9.2	1.3	1.3	NA	1.3	.0	.0	13.8	13.2	14.7
Lu	1.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mg	.0	0.1	.0	> 0.1	0.2	NA	0.1	.0	0.1	85.7	9.9	43.6
Mn	1.1	3.3	0.4	2.3	0.3	NA	0.1	.0	.0	43.3	10.4	12.1
Hg	NA	86.7	20.0	NA	11.6	NA	NA	NA	NA	NA	NA	NA
Mo	1.1	38.8	0.7	3.4	0.8	NA	< 0.1	0.2	< 0.1	30.7	84.2	67.4
Nd	0.2	< 0.3	< 85.3	< 4.1	0.2	NA	NA	NA	NA	NA	NA	NA
Ni	2.2	19.3	2.8	3.0	10.0	4.2E-04	44.7	.0	0.2	115.1	110.3	234.7
Nb	0.2	0.1	1.3	< 2.1	0.2	NA	NA	NA	NA	NA	NA	NA
Os	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pd	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P	.0	1.2	ND	NA	0.1	NA	0.1	.0	.0	47.6	11.7	32.7
Pt	NA	< 27.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
K	.0	7.3	NA	> 0.3	0.2	NA	.0	.0	.0	10.8	12.8	6.5
Pr	.0	< 0.2	< 34.8	< 318.5	0.2	NA	NA	NA	NA	NA	NA	NA
Re	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

(continued)

TABLE A-4. TRACE ELEMENT DISTRIBUTION IN WASTE STREAMS EXPRESSED AS PERCENT OF INPUT (continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha[a] (Ft. Shell.)	Riley		Foster-Wheeler/ STOIC	Luzi-type (Kosovo) Combined Flare Gas	KVW Vapors			KVW Particulates		
			Vapors	Aerosols			Subbituminous	Bituminous	Lignite	Subbituminous	Bituminous	Lignite
Rh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rb	0.5	0.1	3.3	6.9	0.2	NA	NA	NA	NA	NA	NA	NA
Ru	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sm	0.1	NA	< 5.4	< 1.8	0.1	NA	NA	NA	NA	NA	NA	NA
Sc	0.2	ND	< 9.1	< 1.4	0.9	NA	NA	NA	NA	NA	NA	NA
Se	6.8	278.3	> 70.6	NA	1.6	3.0E-03	0.0	0.0	0.0	74.2	4.7	10.9
Si	.0	< 0.1	NA	NA	.0	NA	.0	.0	.0	38.1	10.4	2.6
Ag	4.7	2.0	NA	> 16.3	0.2	NA	NA	NA	NA	ND	NA	NA
Na	.0	.0	0.3	> 0.2	2.2	NA	0.1	.0	.0	51.8	5.8	7.3
Sr	0.1	ND	0.1	> 0.2	0.1	2.0E-04	0.0	0.0	0.0	85.7	28.3	47.7
S	.0	61.1	< 582.1	NA	.0	NA	0.0	0.0	0.0	7.5	2.0	12.8
Ta	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Te	NA	NA	NA	NA	0.2	NA	NA	NA	NA	NA	NA	NA
Tb	0.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tl	<= 10.0	NA	NA	NA	NA	NA	ND[c]	ND	ND	NA	ND	ND
Th	0.1	NA	9.6	< 0.8	0.1	NA	NA	NA	NA	NA	NA	NA
Sn	ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ti	7.7	6.4	NA	> 28.1	12.7	NA	NA	NA	NA	NA	NA	NA
W	0.5	0.1	< 0.2	> 7.2	0.1	NA	.0	.0	.0	59.1	17.3	26.5
U	0.7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
V	0.2	NA	< 10.0	< 0.6	0.2	NA	ND	ND	ND	ND	ND	ND
Yb	0.1	0.3	< 0.2	0.8	0.2	4.1E-04	.0	0.1	.0	58.6	19.4	26.7
Y	0.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Zn	0.3	< 0.1	0.4	1.8	0.1	NA	NA	NA	NA	NA	NA	NA
Zr	0.1	9.2	2.2	< 24.1	11.4	1.9E-03	.0	0.1	.0	11.6	2.6	.0
		1.6	NA	0.9	0.2	NA	NA	NA	NA	NA	NA	NA

[a] Test Burner Flue Gas
[b] NA = Not analyzed.
[c] ND = Not detected.

TABLE A-5. TRACE ELEMENT DISTRIBUTION IN WASTE STREAMS EXPRESSED AS PERCENT OF INPUT

Element	Wellman-Galusha (Ft. Snell.) Cyclone Quench Water	Foster-Wheeler/ SIOIC ESP Oils	Lurgi-(SASOL)[a]		Synthane[b]		Texaco (R/R) Settler Underflow Blowdown
			By-Products	Raw Gas Liquor	Condensate Water	Condensate Tar/Water	
Al	< 0.09	0.01	< 1.0	< 1.0	.0	0.4	5.1
Sb	NA[c]	1.48	23	< 1.0	NA	NA	6.7
As	< 0.08	0.67	19.0	29.0	5.1	1.9	0.6
Ba	< 0.04	0.02	< 1.0	< 1.0	NA	NA	5.8
Be	NA	NA	< 1.0	< 1.0	0.6	33.1	3.5
Bi	NA	NA	NA	NA	4.8	NA	> 8.9
B	0.02	0.06	NA	NA	0.4	0.1	38.2
Br	0.08	0.07	NA	NA	12.7	1.3	6.3
Cd	0.02	NA	> 100.0	< 3.0	NA	NA	39.4
Ca	< 0.03	0.01	< 1.0	< 1.0	.0	0.3	4.2
Ce	< 0.12	0.01	NA	NA	NA	NA	4.2
Cs	< 0.08	NA	NA	NA	NA	NA	5.1
Cl	2.23	0.02	NA	NA	8.3	9.0	3.5
Cr	< 0.10	< 0.03	< 1.0	13.0	0.5	3.7	7.3
Co	NA	< 0.56	5.0	< 1.0	0.1	0.4	7.8
Cu	< 0.09	0.05	< 1.0	< 1.0	NA	NA	10.9
Dy	NA	NA	NA	NA	NA	NA	3.6
Er	NA	NA	NA	NA	NA	NA	0.6
Eu	NA	NA	NA	NA	NA	NA	4.4
F	0.02	0.84	NA	NA	NA	NA	> 17.8
Gd	NA	NA	NA	NA	NA	NA	2.1
Ga	< 0.01	0.02	NA	NA	NA	NA	9.0
Ge	0.02	<= 0.15	NA	NA	2.9	NA	22.2
Au	NA	NA	NA	NA	NA	NA	NA
Hf	NA	NA	NA	NA	NA	NA	3.2
Ho	NA	NA	NA	NA	NA	NA	3.2
I	0.07	0.22	NA	NA	NA	NA	1.1
Ir	NA	NA	NA	NA	NA	NA	NA
Fe	< 0.15	0.07	< 1.0	< 1.0	NA	NA	4.2
La	NA	0.01	NA	NA	NA	NA	4.8
Pb	0.13	0.20	33.0	< 1.0	0.5	2.8	3.0
Li	< 0.08	.00	< 1.0	< 1.0	NA	NA	4.4
Lu	NA	NA	NA	NA	NA	NA	2.5
Mg	< 0.03	< 0.01	< 1.0	< 1.0	.0	0.5	7.0
Mn	< 0.17	0.03	< 1.0	< 1.0	4.5	0.1	5.7
Hg	< 0.13	3.37	22.0	> 100.0	NA	NA	0.0
Mo	< 0.16	0.33	< 1.0	< 1.0	NA	NA	9.1
Nd	NA	NA	NA	NA	NA	NA	3.8
Ni	< 0.15	< 0.10	< 1.0	< 1.0	0.7	0.6	5.3
Nb	NA	NA	NA	NA	NA	NA	3.2

(Continued)

TABLE A-5. (Continued)

Element	Wellman-Galusha (Ft. Snell.) Cyclone Quench Water	Foster-Wheeler/ STOIC ESP Oils	Lurgi (SASOL)[a] By-Products	Lurgi (SASOL)[a] Raw Gas Liquor	Synthane[b] Condensate Water	Synthane[b] Condensate Tar/Water	Texaco (R/R) Settler Underflow Blowdown
Os	NA[c]	NA	NA	NA	NA	NA	NA
Pd	NA	NA	NA	NA	NA	NA	NA
P	< 0.06	.00	NA	NA	.0	6.5	6.2
Pt	NA	NA	NA	NA	NA	NA	NA
K	1.45	0.04	< 1.0	< 1.0	5.6	33.3	7.1
Pr	NA	< 0.01	NA	NA	NA	NA	12.7
Re	< 0.43	NA	NA	NA	NA	NA	NA
Rh	NA	NA	NA	NA	NA	NA	NA
Rb	NA	0.01	NA	NA	NA	0.2	11.3
Ru	NA	NA	NA	NA	NA	NA	NA
Sm	NA	NA	NA	NA	NA	NA	6.3
Sc	NA	< 0.20	NA	NA	0.4	NA	5.1
Se	< 0.42	< 1.24	4.0	100.0	3.7	2.7	70.8
Si	< 0.08	0.01	< 1.0	< 1.0	NA	NA	0.3
Ag	< 0.01	0.36	< 15.0	< 5.0	NA	NA	NA
Na	0.07	0.41	< 1.0	< 1.0	0.1	4.4	7.3
Sr	< 0.03	.00	< 1.0	< 1.0	NA	NA	4.4
S	NA	0.69	NA	NA	6.8	31.2	NA
Ta	NA	NA	NA	NA	NA	NA	1.7
Te	NA	NA	NA	NA	NA	NA	< 1.3
Tb	NA	NA	NA	NA	NA	NA	2.5
Tl	NA	NA	NA	NA	0.2	NA	1.8
Th	NA	NA	NA	NA	NA	NA	1.6
Tm	NA	NA	NA	NA	NA	NA	< 1.3
Sn	12.59	0.14	NA	NA	NA	NA	38.0
Ti	< 0.12	0.01	< 1.0	< 1.0	0.1	0.3	4.8
W	NA	NA	NA	NA	NA	NA	> 25.3
U	NA	NA	NA	NA	NA	NA	4.2
V	< 0.16	0.38	< 1.0	< 1.0	0.2	0.4	7.3
Yb	NA	NA	NA	NA	NA	NA	0.4
Y	< 0.13	NA	NA	NA	NA	NA	3.2
Zn	< 0.13	0.21	2.0	< 1.0	2.0	15.8	17.5
Zr	< 0.10	.00	NA	NA	NA	NA	4.4

[a] Source: Reference 11.
[b] Calculated as percent of detected output. Does not include all streams.
[c] NA = Not analyzed.

TABLE A-6. TRACE ELEMENT DISTRIBUTION IN OTHER STREAMS EXPRESSED AS PERCENT OF INPUT

Lurgi-Type (Kosovo)

Element	Heavy Tar	Light Tar	Medium Oil	Naphtha	Phenosolvan Inlet Water	LP Coal Lock Vent
Al	NA[a]	NA	NA	NA	NA	NA
Sb	0.2	0.7	0.1	9.0E-03	0.14	3.8E-03
As	NA	NA	NA	NA	NA	NA
Ba	0.2	0.2	NA	1.7E-03	0.00	5.3E-04
Be	NA	NA	NA	NA	NA	NA
Bi	NA	NA	NA	NA	NA	NA
B	NA	NA	NA	NA	NA	NA
Br	0.6	0.4	.0	1.9E-04	0.03	8.9E-04
Cd	NA	NA	NA	NA	NA	NA
Ca	NA	NA	NA	NA	NA	NA
Ce	NA	NA	NA	NA	NA	NA
Cs	NA	NA	NA	NA	NA	NA
Cl	0.2	0.1	0.1	1.1E-03	0.02	4.1E-04
Cr	0.3	NA	NA	1.4E-03	NA	1.9E-04
Co	0.1	0.9	.0	3.5E-03	0.02	5.5E-04
Cu	NA	NA	NA	NA	NA	NA
Dy	NA	NA	NA	NA	NA	NA
Er	NA	NA	NA	NA	NA	NA
Eu	NA	NA	NA	NA	NA	NA
F	NA	NA	NA	NA	NA	NA
Gd	NA	NA	NA	NA	NA	NA
Ga	NA	NA	NA	NA	NA	NA
Ge	NA	NA	NA	NA	NA	NA
Au	NA	NA	NA	NA	NA	NA
Hf	NA	NA	NA	NA	NA	NA
Ho	NA	NA	NA	NA	NA	NA
I	NA	NA	NA	NA	NA	NA
Ir	NA	NA	NA	NA	NA	NA
Fe	NA	NA	NA	NA	NA	NA
La	4.9	2.1	0.3	7.5E-03	0.14	1.2E-03
Pb	NA	NA	NA	NA	NA	NA
Li	NA	NA	NA	NA	NA	NA
Lu	NA	NA	NA	NA	NA	NA
Mg	NA	NA	NA	NA	NA	NA
Mn	0.5	NA	0.4	1.7E-01	15.00	9.2E-03
Hg	0.1	NA	.0	1.4E-03	NA	9.5E-04
Mo	NA	NA	NA	NA	NA	NA

(Continued)

TABLE A-6. (Continued)

Element	Heavy Tar	Light Tar	Medium Oil	Naphtha	Phenosolvan Inlet Water	LP Coal Lock Vent
Nd	0.1	0.2	NA	8.8E-04	0.01	1.0E-04
Ni	NA	NA	NA	NA	NA	NA
Nb	NA	NA	NA	NA	NA	NA
Os	NA	NA	NA	NA	NA	NA
Pd	NA	NA	NA	NA	NA	NA
P	NA	NA	NA	NA	NA	NA
Pt	NA	NA	NA	NA	NA	NA
K	NA	NA	NA	NA	NA	NA
Pr	NA	NA	NA	NA	NA	NA
Re	NA	NA	NA	NA	NA	NA
Rh	NA	NA	NA	NA	NA	NA
Rb	NA	NA	NA	NA	NA	NA
Ru	NA	NA	NA	NA	NA	NA
Sm	NA	NA	NA	NA	NA	NA
Sc	0.1	0.2	0.2	3.4E-02	NA	NA
Se	NA	NA	NA	NA	NA	NA
Si	NA	NA	NA	NA	NA	NA
Ag	NA	NA	NA	NA	NA	NA
Na	0.1	0.3	NA	NA	0.04	4.3E-04
Sr	NA	NA	NA	NA	NA	NA
S	NA	NA	NA	NA	NA	NA
Ta	NA	NA	NA	NA	NA	NA
Te	NA	NA	NA	NA	NA	NA
Tb	NA	NA	NA	NA	NA	NA
Tl	NA	NA	NA	NA	NA	NA
Th	NA	NA	NA	NA	NA	NA
Tm	NA	NA	NA	NA	NA	NA
Sn	NA	NA	NA	NA	NA	NA
Ti	NA	NA	NA	NA	NA	NA
W	NA	NA	NA	NA	NA	NA
U	0.3	NA	NA	NA	NA	8.6E-05
V	NA	NA	NA	NA	NA	NA
Yb	NA	NA	NA	NA	NA	NA
Y	0.4	0.5	0.2	9.5E-04	0.16	1.5E-03
Zn	NA	NA	NA	NA	NA	NA
Zr	NA	NA	NA	NA	NA	NA

[a]NA = Not analyzed.

APPENDIX B

MASS BALANCE DATA FOR COAL GASIFICATION TESTS
(PERCENT OF OUTPUT)

These tables present the distributions of trace elements in discharge streams as percentage of output for the Wellman-Galusha (Glen-Gery), STOIC, Riley, Wellman-Galusha (Ft. Snelling) and KRW gasifiers. Discharge streams included gasifier ash, ash sluice water, combined gasifier ash/sluice water, cyclone dust, and product gas.

Gasifier Ash Elemental Distribution

This table gives percent output in gasifier ash compared to trace element output of all streams.

Elemental Distribution in Percent=

$$\frac{\text{elemental flow rate in discharge stream}}{\text{elemental flow rate in all discharge streams}} \times 100$$

Elemental Flow Rate=

(concentration in stream) X (stream flow rate)

TABLE B-1. GASIFIER ASH ELEMENTAL DISTRIBUTION

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft.Snell.)	Riley	Foster-Wheeler/ STOIC	KRW		
					Subbituminous	Bituminous	Lignite
Al	NA[a]	98.1	96.8	99.6	49.8	85.7	50.5
Sb	25.6	12.4	24.6	NA	10.6	14.2	22.4
As	42.5	49.5	64.8	97.2	44.8	64.2	38.2
Ba	NA	96.2	96.8	99.9	19.7	58.8	15.9
Be	99.1	100.0	> 34.3	99.0	ND[b]	NA	ND
Bi	98.9	NA	< 23.1	NA	NA	NA	NA
B	99.6	92.0	52.2	99.0	51.2	87.6	80.2
Br	97.9	58.9	18.1	70.1	NA	NA	NA
Cd	24.9	70.9	NA	99.4	12.1	80.3	90.5
Ca	> 98.8	91.7	94.8	99.4	30.0	89.2	31.3
Ce	99.4	98.1	90.8	99.7	NA	NA	NA
Cs	98.5	95.5	45.0	99.9	NA	NA	NA
Cl	63.2	75.9	3.5	45.2	29.4	52.7	3.3
Cr	99.5	90.2	61.1	94.8	28.0	16.2	52.4
Co	99.1	40.2	91.3	99.6	> 45.3	> 80.3	90.1
Cu	99.0	92.4	89.9	79.4	28.7	83.3	45.9
Dy	97.2	98.8	> 70.9	99.3	NA	NA	NA
Er	98.9	98.6	> 53.6	99.7	NA	NA	NA
Eu	98.4	98.1	> 62.9	98.9	NA	NA	NA
F	95.2	74.2	50.1	90.8	NA	NA	NA
Gd	99.2	98.6	> 73.7	99.5	NA	NA	NA
Ga	78.4	61.8	25.2	88.1	NA	NA	NA
Ge	90.6	52.7	64.9	77.4	NA	NA	NA
Hf	98.5	100.0	> 76.8	99.4	NA	NA	NA
Ho	99.4	98.6	> 60.8	99.7	NA	NA	NA
I	57.0	46.7	6.7	84.5	NA	NA	NA
Fe	> 98.8	98.5	98.5	99.6	63.4	90.0	93.4
La	99.1	98.8	90.1	99.9	NA	NA	NA
Pb	67.9	50.4	29.1	55.9	37.9	5.7	38.2
Li	>= 98.1	97.4	71.1	97.8	48.8	76.5	68.9
Lu	95.7	100.0	> 26.1	100.0	NA	NA	NA
Mg	> 98.8	92.0	97.4	99.8	30.1	86.0	28.1
Mn	91.1	96.9	96.7	99.8	40.9	47.3	90.5
Hg	9.9	28.8	1.2	74.8	NA	NA	NA
Mo	94.5	74.7	72.9	98.0	30.4	51.8	47.7
Nd	96.8	98.6	> 66.3	99.9	NA	NA	NA
Ni	97.5	86.2	85.5	89.9	21.6	22.9	ND
Nb	98.3	97.7	96.7	99.7	NA	NA	NA
P	> 98.8	94.0	> 83.3	98.7	16.0	89.0	79.5
K	> 99.0	96.1	79.2	99.6	68.9	83.4	70.0
Pr	97.9	98.3	> 70.6	99.7	NA	NA	NA

(Continued)

TABLE B-1. (Continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft.Snell.)	Riley	Foster-Wheeler/ SIOIC	KRW		
					Subbituminous	Bituminous	Lignite
Rb	99.6	98.9	68.1	99.8	NA	NA	NA
Sm	99.0	97.8	85.2	99.3	NA	NA	NA
Sc	99.1	96.5	94.7	99.5	NA	NA	NA
Se	55.4	29.2	< 21.6	90.8	27.0	87.3	37.0
Si	> 99.1	98.1	NA	NA	61.3	89.3	92.7
Ag	83.8	54.2	> 43.2	90.4	ND	N	NA
Na	99.0	89.9	58.8	97.3	41.9	77.8	57.2
Sr	99.3	90.3	> 80.8	98.9	NA	NA	NA
S	99.0	21.7	23.6	8.1	NA	NA	NA
Ta	NA	100.0	NA	100.0	NA	NA	NA
Te	< 71.0	NA	< 6.0	94.3	NA	NA	NA
Tb	98.6	98.6	> 59.4	99.1	NA	NA	NA
Tl	36.5	NA	< 23.2	75.3	ND	ND	ND
Th	97.0	98.8	80.7	99.7	NA	NA	NA
Tm	98.9	100.0	> 26.5	100.0	NA	NA	NA
Sn	62.7	18.7	> 56.1	38.2	NA	NA	NA
Ti	94.6	98.6	96.3	99.5	44.0	83.4	67.0
W	96.0	90.5	61.5	97.9	NA	NA	NA
U	98.6	99.2	65.9	99.6	ND	ND	ND
V	99.2	99.1	95.4	99.1	31.0	73.0	64.6
Yb	98.9	97.3	60.4	100.0	NA	NA	NA
Y	99.2	96.9	98.4	99.6	NA	NA	NA
Zn	54.4	43.0	60.6	65.2	48.9	88.6	97.9
Zr	99.7	96.3	96.4	99.6	NA	NA	NA

[a]NA = Not analyzed.
[b]ND = Not detected.

Ash Sluice Water Elemental Distribution

This table gives percent output of trace elements in the ash sluice water compared to output for three gasifiers.

Elemental Distribution in Percent=

$$\frac{\text{elemental flow rate in discharge stream}}{\text{elemental flow rate in all discharge streams}} \times 100$$

Elemental Flow Rate=

(concentration in stream) x (stream flow rate)

TABLE B-2. ASH SLUICE WATER ELEMENTAL DISTRIBUTION

Element	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC
Al	< 0.1	0.2	< .0
Sb	< 0.1	< 3.8	NA[b]
As	< 0.1	0.7	NA
Ba	< 0.1	0.1	.0
Be	NA	< 3.3	NA
Bi	NA	< 3.4	NA
B	< 0.6	36.3	0.2
Br	0.2	5.8	0.6
Cd	< 0.1	NA	NA
Ca	0.1	2.6	0.3
Ce	< 0.1	0.2	NA
Cs	NA	2.4	NA
Cl	10.8	11.3	0.8
Cr	< 0.1	< 0.1	.0
Co	< 0.1	< 0.9	.0
Cu	< 0.1	0.4	.0
Dy	NA	> 1.0	NA
Er	NA	< 2.3	NA
Eu	NA	< 1.8	NA
F	< 0.1	8.3	.0
Gd	NA	< 1.1	NA
Ga	< 0.1	3.2	.0
Ge	NA	< 1.1	NA
Au	NA	NA	NA
Hf	NA	< 1.1	NA
Ho	NA	< 1.8	NA
I	NA	2.4	0.5
Ir	NA	NA	NA
Fe	< 0.1	0.1	NA
La	< 0.1	< 0.2	NA
Pb	< 0.1	< 0.1	.0
Li	0.2	< 0.9	0.1
Lu	NA	< 3.8	NA
Mg	< 0.1	0.2	ND[c]
Mn	< 0.1	0.7	< .0
Hg	< 0.1	< 4.0	2.8
Mo	0.4	18.0	0.2
Nd	NA	< 0.2	NA
Ni	< 0.1	< 0.4	.0
Nb	< 0.1	< 0.2	< .0
Os	NA	NA	NA

(Continued)

TABLE B-2. (Continued)

Element	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC
Pd	NA	NA	NA
P	< 0.1	1.0	NA
Pt	NA	NA	NA
K	0.3	19.8	.0
Pr	< 0.1	< 0.5	NA
Re	NA	NA	NA
Rh	NA	NA	NA
Rb	NA	17.6	.0
Ru	NA	NA	NA
Sm	NA	< 0.5	NA
Sc	NA	< 0.3	NA
Se	< 0.1	< 4.3	< 0.1
Si	< 0.1	NA	NA
Ag	< 0.1	> 6.1	NA
Na	2.2	39.2	0.1
Sr	< 0.1	> 12.9	> 0.3
S	0.6	> 0.3	0.1
Ta	NA	NA	NA
Te	NA	< 0.8	0.5
Tb	NA	< 1.7	NA
Tl	NA	< 3.4	NA
Th	NA	< 0.7	NA
Tm	NA	< 3.9	NA
Sn	29.0	< 0.8	NA
Ti	< 0.1	< .0	ND
W	0.5	9.8	NA
U	NA	< 1.3	.0
V	< 0.1	< 0.1	.0
Yb	NA	< 1.8	NA
Y	NA	< 0.1	.0
Zn	< 0.1	< 0.2	NA
Zr	< 0.1	< 0.1	NA

[a] Calculated as percent of coal input.
[b] NA = Not analyzed.
[c] ND = Not detected.

Gasifier Ash plus Sluice Water Elemental Distribution

Values for Foster-Wheeler/STOIC (UMD), Riley, and Wellman-Galusha (Ft. Snelling) are percent output in ash + percent output in ash sluice water compared to input coal.

Elemental Distribution in Percent=

$$\frac{\text{elemental flow rate in discharge stream}}{\text{elemental flow rate in all discharge streams}} \times 100$$

Elemental Flow Rate=

(concentration in stream) X (stream flow rate)

Wellman-Galusha (Glen-Gery) is without sluice water.

TABLE B-3. GASIFIER ASH + SLUICE WATER ELEMENTAL DISTRIBUTION

Element	Wellman-Galusha[a] (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC
Al	NA[b]	98.1	97.0	99.6
Sb	25.6	12.4	< 28.4	NA
As	42.5	49.5	65.5	97.2
Ba	NA	96.2	96.9	99.9
Be	99.1	100.0	ND[c]	99.0
Bi	98.9	NA	< 26.5	NA
B	99.6	< 92.6	88.5	99.2
Br	97.9	59.1	23.9	70.7
Cd	24.9	70.9	NA	99.4
Ca	> 98.8	91.8	97.4	99.7
Ce	99.4	98.1	91.0	99.7
Cs	98.5	95.5	47.4	99.9
Cl	63.2	86.7	14.8	46.0
Cr	99.5	90.2	< 61.2	94.8
Co	99.1	40.2	< 92.2	99.6
Cu	99.0	92.4	90.3	79.4
Dy	97.2	98.8	> 71.9	99.3
Er	98.9	98.6	ND	99.7
Eu	98.4	98.1	ND	98.9
F	95.2	74.2	58.4	90.8
Gd	99.2	98.6	ND	99.5
Ga	78.4	61.8	28.4	88.1
Ge	90.6	52.7	< 66.0	77.4
Au	NA	NA	NA	NA
Hf	98.5	100.0	< 77.9	99.4
Ho	99.4	98.6	ND	99.7
I	57.0	46.7	9.1	85.0
Ir	NA	NA	NA	NA
Fe	> 98.8	98.5	98.6	99.6
La	99.1	98.8	< 90.3	99.9
Pb	67.9	50.4	< 29.2	55.9
Li	>= 98.1	97.6	< 72.0	97.8
Lu	95.7	100.0	< 29.9	100.0
Mg	> 98.8	92.0	97.6	99.8
Mn	91.1	96.9	97.4	99.8
Hg	9.9	28.8	< 5.2	77.6
Mo	94.5	75.1	90.9	98.2
Nd	96.8	98.6	ND	99.9
Ni	97.5	86.2	< 85.9	89.9
Nb	98.3	97.7	< 96.9	99.7

(Continued)

TABLE B-3. (Continued)

Element	Wellman-Galusha[a] (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC
Os	NA	NA	NA	NA
Pd	NA	NA	NA	NA
P	> 98.8	94.0	> 84.0	98.7
Pt	NA	NA	NA	NA
K	> 99.0	96.4	99.0	99.6
Pr	97.9	98.3	> 71.1	99.7
Re	NA	66.7	NA	NA
Rh	NA	NA	NA	NA
Rb	99.6	98.9	85.7	99.8
Ru	NA	NA	NA	NA
Sm	99.0	97.8	< 85.7	99.3
Sc	99.1	96.5	< 95.0	99.5
Se	55.4	29.2	< 25.9	90.8
Si	> 99.1	98.1	NA	NA
Ag	83.8	54.2	> 49.3	90.4
Na	99.0	92.1	98.0	97.4
Sr	99.3	90.3	> 93.7	99.2
S	99.0	22.3	> 23.9	8.2
Ta	NA	100.0	NA	100.0
Te	< 71.0	NA	< 6.8	94.9
Tb	98.6	98.6	ND	99.1
Tl	36.5	NA	< 26.6	75.3
Th	97.0	98.8	< 81.4	99.7
Tm	98.9	100.0	ND	100.0
Sn	62.7	47.7	ND	38.2
Ti	94.6	98.6	96.3	99.5
W	96.0	91.0	71.3	97.9
U	98.6	99.2	< 67.2	99.6
V	99.2	99.1	95.4	99.2
Yb	98.9	97.3	< 62.2	100.0
Y	99.2	96.9	98.4	99.7
Zn	54.4	43.0	< 60.8	65.2
Zr	99.7	96.3	< 96.5	99.6

[a] Calculated as percent of coal input.
[b] NA = Not analyzed.
[c] ND = Not detected.

Cyclone Dust Elemental Distribution

This table gives the percent output of the trace elements compared to total output in four plants and gives percent output in the filter fines of the Synthane plant.

Elemental Distribution in Percent=

$$\frac{\text{elemental flow rate in discharge stream}}{\text{elemental flow rate in all discharge streams}} \times 100$$

Elemental Flow Rate=

(concentration in stream) X (stream flow rate)

The above was used for Wellman-Galusha (Glen-Gery), Foster-Wheeler/STOIC (UMD), and Riley.

For Wellman-Galusha (Ft. Snelling), the elemental distribution value is for the cyclone dust and the cyclone quench water.

For Synthane, the elemental distribution value is an average of runs #293, #294, and #295. The value is determined from: (elemental flow rate in the filter fines)/(the elemental flow rate in all discharge streams except gas).

TABLE B-4. CYCLONE DUST ELEMENTAL DISTRIBUTION

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha[a] (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	Synthane (filter fines)[b]
Al	NA[c]	1.8	2.6	0.2	1.1
Sb	25.6	1.7	1.4	NA	5.4
As	11.0	14.7	3.9	0.7	4.5
Ba	NA	3.3	2.5	0.1	1.0
Be	0.7	< 0.1	> 4.2	0.5	22.2
Bi	0.2	100.0	1.2	NA	33.3
B	0.4	6.9	1.8	0.1	18.3
Br	1.7	37.2	1.0	1.0	6.9
Cd	1.0	24.5	NA	0.3	4.8
Ca	NA	7.8	1.8	0.1	0.8
Ce	0.5	1.8	2.5	0.2	3.2
Cs	1.3	1.2	3.6	0.1	3.7
Cl	7.5	4.2	0.2	2.2	2.3
Cr	0.3	1.4	5.4	0.3	2.1
Co	0.4	1.2	2.5	0.2	3.1
Cu	0.3	4.9	3.3	0.3	NA
Dy	0.6	1.2	> 7.6	0.4	3.2
Er	0.8	1.4	> 3.3	0.2	1.9
Eu	0.9	1.9	> 3.3	0.6	2.1
F	3.6	15.7	2.3	> 4.7	NA
Gd	0.4	1.4	> 3.9	0.3	1.3
Ga	7.3	35.6	11.0	6.2	2.6
Ge	9.1	44.5	1.7	11.8	6.6
Au	NA	NA	NA	NA	NA
Hf	1.4	NA	> 1.0	0.6	1.9
Ho	0.5	1.4	> 3.2	0.1	2.0
I	42.3	13.5	0.8	6.8	18.4
Ir	NA	NA	NA	NA	NA
Fe	0.9	1.4	1.3	0.2	NA
La	0.8	1.0	2.5	0.1	2.7
Pb	12.0	11.3	7.3	22.6	18.6
Li	0.6	1.7	6.3	0.2	NA
Lu	0.9	NA	0.7	NA	1.4
Mg	0.9	7.7	2.3	0.1	1.4
Mn	7.2	1.2	1.4	0.1	0.6
Hg	90.1	5.2	1.5	1.1	NA
Mo	3.4	1.4	2.4	0.3	3.9
Nd	2.9	1.4	3.9	0.1	2.4
Ni	0.7	0.7	3.4	0.3	4.0
Nb	1.4	2.2	1.7	0.2	2.8
Os	NA	NA	NA	NA	NA

(Continued)

TABLE B-4. (Continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha[a] (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	Synthane (filter fines)[b]
Pd	NA	NA	NA	NA	NA
P	0.9	4.0	> 4.4	0.6	0.9
Pt	NA	NA	NA	NA	NA
K	0.9	2.2	> 0.6	0.2	2.0
Pr	2.0	1.7	4.7	0.2	1.9
Re	NA	NA	NA	NA	NA
Rh	0.1	NA	NA	NA	NA
Rb	NA	0.9	6.8	0.1	5.1
Ru	0.9	NA	NA	NA	NA
Sm	0.7	2.2	3.6	0.4	2.1
Sc	4.0	3.5	0.9	0.3	3.9
Se	0.5	4.0	< 1.4	2.3	1.2
Si	3.8	1.9	NA	NA	1.3
Ag	0.9	25.2	< 0.1	< 3.3	NA
Na	0.5	7.5	1.6	0.3	0.8
Sr	0.9	9.5	> 4.3	0.4	1.6
S	NA	3.8	1.3	0.2	1.2
Ta	NA	NA	NA	NA	NA
Te	NA	100.0	0.2	2.7	1.6
Tb	0.9	1.4	> 6.3	0.3	1.1
Tl	24.7	100.0	6.2	12.9	13.1
Th	2.9	1.2	1.0	0.2	2.7
Tm	0.9	NA	0.7	NA	1.5
Sn	11.3	10.3	> 1.2	31.8	5.8
Ti	0.8	1.3	2.9	0.3	1.2
W	2.2	9.0	3.3	1.1	4.1
U	1.3	0.7	1.8	0.2	1.7
V	0.7	0.6	3.1	0.2	2.0
Yb	0.9	2.7	2.9	NA	1.0
Y	0.7	3.1	0.6	0.2	1.8
Zn	22.9	49.8	6.1	14.8	6.3
Zr	0.3	2.1	1.9	0.2	3.6

[a] Cyclone dust + cyclone quench water.
[b] Gas stream not considered in calculation.
[c] NA = Not analyzed.

Product Gas Elemental Distribution

This table gives the percent output of trace elements in the product gas compared to total output of four gasifiers. The values for the Wellman-Galusha (Ft. Snelling) gasifier are from test burner flue gas. Riley values are separated into vapor values and aerosol values.

Elemental distribution in Percent=

$$\frac{\text{elemental flow rate in discharge stream}}{\text{elemental flow rate in all discharge streams}} \times 100$$

Elemental flow rate=

(concentration in stream) X (stream flow rate)

TABLE B-5. PRODUCT GAS ELEMENTAL DISTRIBUTION

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha[a] (Ft. Snell.)	Riley		Foster-Wheeler/ SIOIC	KRW Vapors			KRW Particulate		
			Vapors	Aerosols		Subbituminous	Bituminous	Lignite	Subbituminous	Bituminous	Lignite
Al	NA[b]	< 0.1	0.3	ND[c]	0.2	0.0	.0	.0	50.2	14.3	49.5
Sb	48.7	85.8	< 13.7	56.6	NA	0.0	0.0	0.0	89.4	85.8	77.6
As	> 46.6	35.8	6.0	> 24.7	1.7	0.0	0.0	0.0	55.2	35.8	61.8
Ba	NA	0.5	0.1	> 0.5	0.1	0.1	0.1	0.6	80.3	41.0	83.5
Be	0.1	NA	< 53.7	< 4.5	0.5	ND[c]	0.6	.0	> 98.6	99.4	> 23.5
Bi	0.9	NA	< 55.4	< 16.9	NA	NA	NA	NA	NA	NA	NA
B	< 0.1	0.4	8.3	1.5	0.7	10.2	1.0	0.5	38.6	11.4	19.3
Br	0.4	3.4	73.2	2.0	28.0	NA	NA	NA	NA	NA	NA
Cd	74.0	4.5	NA	NA	0.3	7.2	0.1	.0	80.7	19.6	9.4
Ca	NA	0.4	0.7	ND	0.1	0.1	.0	0.1	69.9	10.8	68.6
Ce	0.1	0.1	< 4.4	2.1	0.2	NA	NA	NA	NA	NA	NA
Cs	0.1	3.3	36.0	12.9	0.1	NA	NA	NA	NA	NA	NA
Cl	> 29.2	4.3	> 84.3	0.7	51.7	0.0	0.0	0.0	70.6	47.3	96.7
Cr	0.2	8.4	NA	31.0	0.5	.0	.0	.0	72.0	83.7	47.6
Co	0.5	58.5	< 3.6	< 1.8	0.2	< 0.2	< 0.2	< 0.1	> 54.5	> 19.5	9.9
Cu	0.6	2.7	< 0.3	6.3	20.2	.0	0.1	.0	71.3	16.6	54.1
Dy	2.2	NA	< 17.0	< 3.5	0.4	NA	NA	NA	NA	NA	NA
Er	< 0.3	NA	< 37.1	< 3.8	0.2	NA	NA	NA	NA	NA	NA
Eu	0.6	NA	< 29.7	< 3.2	0.5	NA	NA	NA	NA	NA	NA
F	1.2	9.9	34.2	5.0	4.2	NA	NA	NA	NA	NA	NA
Gd	0.4	NA	< 17.7	< 3.6	0.3	NA	NA	NA	NA	NA	NA
Ga	> 14.3	2.5	45.8	14.9	5.7	NA	NA	NA	NA	NA	NA
Ge	0.3	2.7	6.3	26.0	10.8	NA	NA	NA	NA	NA	NA
Au	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hf	0.1	NA	< 18.4	< 2.6	NA	NA	NA	NA	NA	NA	NA
Ho	0.1	NA	< 29.2	< 5.0	0.1	NA	NA	NA	NA	NA	NA
I	0.6	39.4	86.7	< 3.3	6.3	NA	NA	NA	NA	NA	NA
Ir	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fe	0.3	0.1	.0	> .0	0.2	.0	0.0	0.1	36.6	10.0	6.5
La	0.1	0.2	< 4.4	2.8	0.1	NA	NA	NA	NA	NA	NA
Pb	20.1	38.0	19.9	43.6	21.3	0.0	0.0	0.0	62.1	94.3	61.8
Li	1.3	0.7	19.0	2.7	1.9	4.3	.0	.0	46.9	23.5	31.1
Lu	3.3	NA	< 62.7	< 6.6	NA	NA	NA	NA	NA	NA	NA
Mg	0.3	0.2	.0	> 0.1	0.1	0.1	.0	0.1	69.8	14.0	71.7
Mn	1.7	1.9	0.2	1.1	0.1	0.1	0.1	.0	59.0	52.6	9.5
Hg	NA	66.0	94.5	NA	16.5	NA	NA	NA	NA	NA	NA
Mo	2.2	23.5	1.1	5.6	0.1	< 0.3	0.1	0.1	69.4	48.1	52.3
Nd	0.3	< 0.1	< 28.3	< 1.4	0.1	NA	NA	NA	NA	NA	NA
Ni	1.8	13.2	5.1	5.6	9.8	21.9	.0	> .0	56.4	77.1	> 65.5
Nb	0.3	0.1	0.6	< 0.9	0.1	NA	NA	NA	NA	NA	NA
Os	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pd	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P	0.3	2.0	9.7	> 1.6	0.7	0.2	.0	.0	83.9	11.0	20.4
Pt	NA	100.0	NA	NA	NA	NA	NA	NA	NA	NA	NA
K	0.1	1.5	18.0	< 0.4	0.2	.0	.0	.0	31.1	16.6	30.0
Pr	.0	< 0.1	< 22.1	< 2.0	0.2	NA	NA	NA	NA	NA	NA
Re	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

(continued)

TABLE B-5. PRODUCT GAS ELEMENTAL DISTRIBUTION (Continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha[a] (Pt. Shell.)	Riley Vapors	Riley Aerosols	Foster-Wheeler/ SIOIC	KRW Vapors Subbituminous	KRW Vapors Bituminous	KRW Vapors Lignite	KRW Particulate Subbituminous	KRW Particulate Bituminous	KRW Particulate Lignite
Rh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rb	0.3	0.2	2.4	5.1	0.1	NA	NA	NA	NA	NA	NA
Ru	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sm	0.1	NA	< 8.1	< 2.7	0.4	NA	NA	NA	NA	NA	NA
Sc	0.2	< 0.1	< 3.6	< 0.6	0.3	NA	NA	NA	NA	NA	NA
Se	40.5	66.8	> 69.0	< 3.7	6.9	0.0	0.0	0.0	73.0	12.7	63.0
Si	.0	< 0.1	NA	NA	NA	.0	.0	0.1	38.7	10.7	7.2
Ag	12.4	20.5	< 33.4	17.3	3.0	NA	NA	NA	NA	NA	NA
Na	0.1	0.2	0.2	> 0.2	2.0	0.1	0.1	0.1	58.0	22.2	42.7
Sr	0.1	< 0.1	0.6	> 1.3	0.4	NA	NA	NA	NA	NA	NA
S	0.1	74.0	74.8	> 0.1	90.9	NA	NA	NA	NA	NA	NA
Ta	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Te	NA	NA	92.2	< 0.8	2.4	NA	NA	NA	NA	NA	NA
Tb	0.4	NA	< 28.5	< 4.0	0.4	NA	NA	NA	NA	ND	ND
Tl	38.8	NA	< 55.7	< 11.5	11.8	ND	ND	ND	ND	NA	NA
Th	0.1	NA	16.1	< 1.4	0.2	NA	NA	NA	NA	NA	NA
Tm	< 0.2	NA	< 63.7	< 5.1	NA	NA	NA	NA	NA	NA	NA
Sn	26.0	14.1	< 13.5	> 28.4	29.7	NA	NA	NA	NA	16.6	33.0
Ti	4.5	0.1	ND	> 0.8	0.2	.0	.0	.0	56.0	NA	NA
W	1.7	NA	< 14.8	< 10.7	1.0	NA	NA	NA	NA	ND	ND
U	0.1	< 0.1	< 29.3	< 1.8	0.2	ND	ND	ND	ND	26.9	35.4
V	0.1	0.2	< 0.3	1.1	0.2	.0	0.1	0.1	68.9	NA	NA
Yb	0.2	NA	< 29.0	< 6.0	NA	NA	NA	NA	NA	NA	NA
Y	0.1	< 0.1	0.2	0.8	0.2	NA	NA	NA	NA	11.1	< 1.3
Zn	17.6	7.2	2.8	> 30.3	19.7	.0	0.3	0.8	51.1	NA	NA
Zr	0.1	1.6	1.0	0.5	0.2	NA	NA	NA	NA	NA	NA

[a]Cyclone dust + cyclone quench water.
[b]NA = not analyzed.
[c]ND = not detected.

APPENDIX C

ENRICHMENT FACTOR CALCULATIONS FOR GASIFIER
ASH AND CYCLONE DUST

Gasifier Ash Enrichment Factors

This table contains the enrichment factors for the gasifier ash of the Wellman-Galusha (Glen-Gery), Foster-Wheeler/STOIC (UMD), Wellman-Galusha (Ft. Snelling), and KRW gasifiers. The values from each plant are included in the averages and standard deviations.

Enrichment Factor=

$$\frac{\text{element concentration in waste}}{\text{element concentration in coal}} \times \frac{\text{ash content in coal}}{\text{ash content in waste}}$$

TABLE C-1. GASIFIER ASH ENRICHMENT FACTORS

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Snell.)	Riley	Foster-Wheeler/ STOIC	KRW			Average	Standard Deviation
					Subbituminous	Bituminous	Lignite		
Al	NA[a]	1.5	1.2	0.7	2.1	0.7	0.7	1.1	0.6
Sb	0.1	< 1.0	0.3	0.1	1.1	0.1	0.5	0.5	0.4
As	0.1	0.7	0.4	1.6	1.2	0.3	0.6	0.7	0.5
Ba	NA	0.6	1.4	0.8	0.7	0.2	0.1	0.6	0.5
Be	0.6	3.2	0.6	0.4	.0	NA	4.3	1.5	1.8
Bi	10.7	NA	0.3	0.1	NA	NA	NA	3.7	6.1
B	0.6	1.2	0.5	3.4	1.2	0.2	0.2	1.1	1.1
Br	0.4	0.3	0.6	0.2	NA	NA	NA	0.4	0.2
Cd	0.2	0.3	< 0.2	0.6	0.8	3.1	16.3	3.1	5.9
Ca	NA	0.5	1.4	1.8	1.1	0.4	0.4	1.0	0.6
Ce	2.9	2.1	1.8	1.1	NA	NA	NA	2.0	0.8
Cs	1.8	1.3	NA	3.3	NA	NA	NA	2.1	1.0
Cl	0.1	0.7	0.5	.0	.0	.0	.0	0.2	0.3
Cr	1.5	1.5	ND[b]	1.0	1.6	0.1	0.6	0.9	0.7
Co	1.4	1.8	1.1	0.9	1.4	0.4	6.7	2.0	2.1
Cu	1.4	1.5	1.0	0.8	1.1	0.4	0.6	1.0	0.4
Dy	1.1	> 10.3	> 3.0	3.7	NA	NA	NA	4.5	4.0
Er	0.9	> 4.4	> 4.0	1.8	NA	NA	NA	2.0	1.6
Eu	0.9	2.2	> 1.8	0.6	NA	NA	NA	1.4	0.8
F	0.2	0.1	1.3	2.0	NA	NA	NA	0.9	0.9
Gd	1.2	1.5	> 2.1	2.4	NA	NA	NA	1.8	0.6
Ga	0.5	0.1	1.9	0.6	NA	NA	NA	0.7	0.8
Ge	0.4	0.2	> 6.6	0.4	NA	NA	NA	1.9	3.1
Au	NA	NA	0.2	NA	NA	NA	NA	0.2	0.0
Hf	NA	> 1.5	1.4	1.2	NA	NA	NA	1.4	0.1
Ho	1.2	> 5.9	> 1.8	2.4	NA	NA	NA	2.8	2.1
I	.0	0.1	0.3	0.1	NA	NA	NA	0.1	0.1
Ir	NA	NA	0.3	NA	NA	NA	NA	0.3	0.0
Fe	NA	2.6	0.5	1.3	2.3	0.6	0.7	1.4	0.9
La	4.1	2.6	2.7	2.4	NA	NA	NA	3.0	0.7
Pb	0.3	0.4	0.5	0.5	1.9	0.1	0.2	0.5	0.6
Li	>= 0.9	1.4	3.2	0.6	0.5	0.4	0.7	1.1	1.0
Lu	0.5	> 0.4	0.3	0.2	NA	NA	NA	0.4	0.1
Mg	NA	0.5	1.3	2.0	1.2	0.6	0.4	1.0	0.6
Mn	1.1	2.9	3.2	2.2	1.0	0.1	2.6	1.9	1.1
Hg	0.1	0.6	.0	0.5	NA	NA	NA	0.3	0.3
Mo	0.9	2.2	0.8	0.7	0.5	0.9	1.4	1.0	0.6
Nd	1.5	4.4	3.7	2.6	NA	NA	NA	3.0	1.3
Ni	2.2	2.2	0.8	0.8	1.5	0.3	< 2.7	1.5	0.9
Nb	1.2	2.2	3.2	1.2	NA	NA	NA	2.0	1.0
Os	NA	NA	0.3	NA	NA	NA	NA	0.3	0.0
Pd	NA	NA	0.3	NA	NA	NA	NA	0.3	0.0
P	>= 0.3	1.0	> 0.3	0.1	0.3	1.0	2.8	0.8	0.9
Pt	NA	NA	0.3	NA	NA	NA	NA	0.3	0.0
K	NA	0.9	1.1	1.0	0.8	0.6	0.3	0.8	0.3
Pr	1.4	3.4	5.4	1.0	NA	NA	NA	2.8	2.0
Re	NA	NA	0.3	NA	NA	NA	NA	0.3	0.0

(continued)

TABLE C-1. GASIFIER ASH ENRICHMENT FACTORS (Continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Pt. Shell.)	Riley	Foster-Wheeler/ STOIC	KRW			Average	Standard Deviation
					Subbituminous	Bituminous	Lignite		
Rh	NA	NA	0.3	NA	NA	NA	NA	0.3	0.0
Rb	3.3	0.8	2.6	1.8	NA	NA	NA	2.1	1.1
Ru	NA	NA	0.3	NA	NA	NA	NA	0.3	0.0
Sm	1.0	1.9	2.2	0.4	NA	NA	NA	1.4	0.8
Sc	1.6	0.6	2.1	0.2	NA	NA	NA	1.1	0.9
Se	0.2	2.2	0.4	0.2	0.9	0.3	0.1	0.6	0.7
Si	NA	1.4	0.2	0.1	2.0	0.9	0.7	0.9	0.7
Ag	0.6	0.1	0.2	.0	> 0.2	NA	NA	0.2	0.2
Na	NA	0.4	1.2	1.0	1.3	0.2	0.2	0.7	0.5
Sr	2.2	0.4	> 0.2	0.1	1.3	0.7	0.6	0.8	0.7
S	NA	0.3	0.3	0.1	0.2	0.2	0.4	0.2	0.1
Ta	NA	NA	0.3	0.4	NA	NA	NA	0.3	.0
Te	NA	NA	0.5	0.1	NA	NA	NA	0.2	0.3
Tb	1.1	1.5	> 3.0	0.6	NA[b]	NA	NA	1.5	1.0
Tl	<= 0.2	NA	0.3	0.2	ND[b]	ND	ND	0.2	0.1
Th	1.7	> 3.4	1.3	0.9	NA	NA	NA	1.8	1.1
Tm	> 0.4	> 0.6	0.4	0.1	NA	NA	NA	0.4	0.2
Sn	0.4	0.1	> 1.1	0.1	NA	NA	NA	0.4	0.5
Ti	NA	2.1	1.2	0.5	1.6	0.9	1.2	1.2	0.5
W	0.7	> 1.5	3.0	1.2	NA	NA	NA	1.6	1.0
U	2.8	> 2.4	2.8	0.8	ND	ND	ND	2.2	1.0
V	2.0	2.8	1.1	0.8	0.9	0.5	1.1	1.3	0.8
Yb	0.6	> 4.4	> 2.4	1.2	NA	NA	NA	2.2	1.7
Y	1.4	2.2	2.4	0.4	NA	NA	NA	1.6	0.9
Zn	0.2	1.0	0.7	0.4	0.4	0.2	.0	0.4	0.3
Zr	2.2	1.5	3.7	0.8	NA	NA	NA	2.0	1.2

[a] NA = Not analyzed.
[b] ND = Not detected.

Cyclone Dust Enrichment Factors

This table gives the enrichment factors for the Wellman-Galusha (Glen-Gery), Foster-Wheeler/STOIC (UMD), Riley, Wellman-Galusha (Ft. Snelling), Synthane (filter fines), and KRW gasifier cyclone dusts. Enrichment factors >1 imply enrichment of an element in the cyclone dust.

Enrichment Factor=

$$\frac{\text{element concentration in waste}}{\text{element concentration in coal}} \times \frac{\text{ash content of coal}}{\text{ash content of waste}}$$

Average and standard deviation exclude Synthane.

TABLE C-2. CYCLONE DUST ENRICHMENT FACTORS

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Pt. Shall.)	Riley	Foster-Wheeler/ STOIC	Synthane[a]	KRW Raw Product Gas Particulates			Average	Standard Deviation
						Subbituminous	Bituminous	Lignite		
Al	NA[b]	0.8	1.2	0.7	1.0	1.9	1.0	0.7	1.0	0.4
Sb	31.4	< 3.9	0.4	33.9	5.7	8.4	3.9	0.5	11.0	13.6
As	8.1	5.7	0.8	6.1	6.2	1.3	1.4	0.6	3.8	3.0
Ba	NA	0.6	1.2	0.3	1.1	2.4	1.1	0.1	1.0	0.8
Be	1.3	0.6	0.3	1.0	2.4	1.9	1.5	4.3	1.7	1.3
Bi	4.7	> 1.8	> 0.4	7.1	NA	NA	NA	NA	3.5	3.0
B	0.6	2.6	0.6	1.4	NA	0.8	0.2	0.2	0.9	0.8
Br	1.7	5.3	0.6	1.3	11.0	NA	NA	NA	4.0	4.3
Cd	3.2	2.9	ND[c]	1.1	6.5	4.6	6.8	16.3	5.2	5.1
Ca	NA	1.3	0.9	1.3	NA	2.3	0.4	0.4	1.1	0.7
Ce	4.3	1.1	1.6	0.9	NA	NA	NA	NA	2.0	1.6
Cs	7.1	0.5	NA	0.8	NA	NA	NA	NA	2.8	3.7
Cl	2.6	1.0	0.9	1.1	NA	.0	.0	.0	0.8	1.0
Cr	1.2	0.6	4.0	1.4	1.6	3.7	7.0	0.6	2.5	2.2
Co	1.6	1.5	1.1	1.0	4.1	1.5	1.0	6.7	2.3	2.0
Cu	1.3	2.2	1.2	1.6	9.3	2.4	0.7	0.6	2.4	2.8
Dy	1.9	> 3.5	> 8.1	7.1	NA	NA	NA	NA	5.2	2.9
Er	2.1	> 1.8	> 1.6	1.4	NA	NA	NA	NA	1.7	0.3
Eu	2.4	1.2	> 1.2	1.8	NA	NA	NA	NA	1.6	0.6
F	2.5	0.8	0.9	> 51.1	NA	NA	NA	NA	13.8	24.9
Gd	1.6	0.6	> 2.4	3.6	0.8	NA	NA	NA	1.8	1.2
Ga	13.0	1.0	1.8	20.0	4.7	NA	NA	NA	8.1	8.2
Ge	10.4	5.1	> 4.0	33.9	11.0	NA	NA	NA	12.9	12.2
Au	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
Hf	NA	NA	> 1.0	3.6	1.5	NA	NA	NA	2.0	1.4
Ho	1.6	> 2.4	> 2.0	1.8	NA	NA	NA	NA	1.9	0.4
I	5.7	1.2	0.6	3.6	14.0	NA	NA	NA	5.0	5.4
Ir	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
Fe	NA	1.1	0.2	1.2	0.8	1.2	0.6	0.7	0.8	0.3
La	8.8	0.8	2.4	0.8	NA	NA	NA	NA	3.2	3.8
Pb	13.6	2.4	4.5	103.6	3.8	2.7	18.9	0.2	18.7	34.9
Li	1.7	0.7	2.1	0.8	NA	0.4	1.2	0.7	1.1	0.6
Lu	1.4	NA	0.2	NA	NA	NA	NA	NA	0.8	0.9
Mg	NA	1.1	1.0	1.1	2.7	2.5	0.9	0.4	1.4	0.9
Mn	24.5	1.0	1.6	0.7	NA	1.3	1.0	2.6	4.7	8.8
Hg	315.8	> 3.5	.0	3.8	NA	NA	NA	NA	80.8	156.7
Mo	9.0	1.2	0.8	0.9	7.3	0.9	7.7	1.4	3.6	3.6
Nd	13.0	1.8	5.1	0.8	NA	NA	NA	NA	5.2	5.6
Ni	4.5	0.5	1.2	1.3	3.0	3.4	10.1	2.7	3.3	3.0
Nb	4.9	1.5	1.8	0.9	NA	NA	NA	NA	2.3	1.8
Os	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
Pd	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
P	> 0.7	1.2	0.5	0.4	NA	1.4	1.1	2.8	1.1	0.8
Pt	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
K	NA	0.5	1.4	1.0	3.1	0.3	1.2	0.3	1.1	1.0
Pr	8.3	1.7	4.3	0.9	NA	NA	NA	NA	3.8	3.3
Re	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0

(continued)

TABLE C-2. CYCLONE DUST ENRICHMENT FACTORS (Continued)

Element	Wellman-Galusha (Glen-Gery)	Wellman-Galusha (Ft. Shell.)	Riley	Foster-Wheeler/ STOIC	Synthane[a]	KRW Raw Product Gas Particulates			Average	Standard Deviation
						Subbituminous	Bituminous	Lignite		
Rh	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
Rb	0.9	0.2	6.3	0.8	6.5	NA	NA	NA	2.9	3.2
Ru	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
Sm	2.6	1.2	1.3	0.7	NA	NA	NA	NA	1.5	0.8
Sc	3.3	0.6	0.5	0.4	NA	NA	NA	NA	1.2	1.4
Se	3.8	8.2	0.7	2.6	NA	2.2	0.4	0.1	2.6	2.8
Si	NA	0.7	0.3	0.4	1.2	1.1	0.9	0.7	0.8	0.3
Ag	7.9	1.2	.0	0.9	NA	ND[c]	NA	NA	2.1	3.3
Na	NA	0.9	1.0	1.4	2.0	1.5	0.5	0.2	1.1	0.6
Sr	3.3	1.2	> 0.3	0.3	1.2	2.5	2.6	0.6	1.5	1.1
S	NA	1.6	0.5	0.7	NA	0.2	0.2	0.4	0.6	0.5
Ta	NA	NA	0.2	NA	NA	NA	NA	NA	0.2	0.0
Te	>= 2.1	> 1.2	0.2	0.9	NA	NA	NA	NA	1.1	0.8
Tb	2.8	0.6	> 4.0	1.4	NA	NA	NA	NA	2.2	1.5
Tl	<= 34.7	> 5.3	> 2.0	21.4	NA	ND	ND	ND	15.9	15.2
Th	15.3	> 1.2	0.3	0.7	NA	NA	NA	NA	4.4	7.3
Tm	> 0.9	NA	0.2	NA	NA	NA	NA	NA	0.6	0.5
Sn	18.5	2.4	> 1.0	68.6	3.3	NA	NA	NA	18.7	28.8
Ti	NA	0.8	1.2	0.6	1.1	1.7	1.6	1.2	1.2	0.4
W	4.7	NA	4.0	7.1	NA	NA	NA	NA	5.3	1.6
U	10.7	> 0.6	0.4	0.8	NA	ND	ND	ND	3.1	5.0
V	3.9	0.5	1.3	0.9	NA	1.7	1.8	1.1	1.6	1.1
Yb	1.6	> 3.5	> 1.8	NA	NA	NA	NA	NA	2.3	1.1
Y	2.8	1.9	0.5	0.4	NA	NA	NA	NA	1.4	1.2
Zn	> 29.6	31.2	2.5	43.2	7.0	0.3	0.2	.0	14.3	17.5
Zr	1.9	1.0	1.0	0.6	NA	NA	NA	NA	1.1	0.5

[a] Not included in average and/or standard deviation.
[b] NA = Not analyzed.
[c] ND = Not detected.

APPENDIX D

GASIFIER FLOW RATE DATA

TABLE D-1. CHAPMAN GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier[a]
Inputs:	
Coal	152
Air	385
Steam (water vapor)	80
Outputs:	
Cooled product gas	495
Gasifier ash (dry basis)	9.3
Cyclone dust	0.8
By-product tar	15

[a]Average for the two operating gasifiers.
Source: 1

TABLE D-2. WELLMAN-GALUSHA (FORT SNELLING) GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier	
	Sampling Period One	Sampling Period Two
Inputs:		
Coal	320 ± 28	250 ± 21
Air	500 ± 55	444 ± 49
Steam (water vapor)	67 ± 8.4	66 ± 8.3
Outputs:		
Dry product gas	720 ± 63	570 ± 49
Product gas moisture	130 ± 16	120 ± 15
Tar	12 ± 1.4	9.8 ± 1.1
Gasifier ash	27 ± 2.8	21 ± 2.1
Cyclone dust	3.8 ± 1.3	—
Gasifier ash sluice water	~7	~7
Cyclone dust quench water	<7	

Source: 3

TABLE D-3. WELLMAN-GALUSHA (GLEN-GERY) STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal	219
Air	992
Steam (water vapor)	194
Outputs:	
Product gas	1,333
Gasifier ash	20.6
Cyclone dust	0.2
Coal hopper gas	2.2
Pokehole gas	1.7

Source: 2

TABLE D-4. RILEY GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal (including moisture)	1,000 ± 109
Air	1,200 ± 240
Steam	350 ± 88
Service water	2,200 ± 440
Outputs:	
Product gas (dry basis)	2,300 ± 230
Moisture in gas	620 ± 61
Gasifier ash	75 ± 30
Cyclone dust	4 ± 1
Tars and oils	21 ± 4
Ash pan water	2,200 ± 440

Source: 4

TABLE D-5. FOSTER-WHEELER/STOIC GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal (including moisture)	300 ± 30
Air	620 ± 120
Steam (water vapor)	70 ± 7
Ash pan makeup water	7 ± 4
Lock hopper purge steam	16 ± 4
Pokehole purge steam	6 ± 2
Outputs:	
Combined product gas (dry basis)	930 ± 190
Moisture in product gas	75 ± 15
Gasifier ash	35 ± 4
Moisture in gasifier ash	9 ± 0.9
Cyclone dust	0.2 ± 0.1
ESP oil	4 ± 1

Source: 5

TABLE D-6. LURGI-TYPE GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
COAL PREPARATION	
Run-of-mine coal	6,667
Dryer offgas (dry basis)	22
Dryer condensate	-
Dried coal	4,444
GASIFICATION/GAS QUENCH	
Dried coal	4,444
Oxygen	778
Steam	3,611
High pressure coal lock vent (dry basis)	65
Low pressure coal lock vent (dry basis)	5.6
Ash lock cyclone vent (dry basis)	12.4
Wet ash	750
Ash quench wastewater	720
Crude gas (dry basis)	4,675
RECTISOL AGR	
Crude gas (dry basis)	4,675
Clean product gas (dry basis)	1,275
H_2S-rich offgas (dry basis)	1,758
CO_2-rich offgas (dry basis)	1,725
Cyanic water	172
Naphtha	36
GAS LIQUOR SEPARATION	
Cyanic water	172
Heavy tar	28
Waste gas (dry basis)	12.4
Medium oil	69
Light tar	111
Phenolic water	3,611
PHENOSOLVAN/STRIPPING	
Phenolic water	3,611
Crude phenol	25
NH_3 stripper vent gas	96.5

Source: 7

TABLE D-7. KRW PDU GASIFIER STREAM FLOW DATA

Stream	Flow Rate, g/s-gasifier		
	Test 1 Wyoming Subbituminous	Test 2 Pittsburgh No. 8	Test 3 North Dakota Lignite
Inputs			
Coal	219.2	141.0	271.6
Steam	56.8	73.4	67.2
Oxygen	112.8	145.3	135.6
CO_2 to gasifier	50.8	65.7	49.2
H_2O injection	0.0	150.3	0.0
Coal lockhopper gas (CO_2)	4.0	2.6	5.0
Ash lockhopper gas (CO_2)	1.7	1.7	1.7
Makeup water	479.4	207.9	161.3
Outputs			
Scrubbed and cooled product gas	364.0	321.9	453.8
Gasifier ash	11.6	16.0	15.6
Wastewater	506.1	408.1	202.4
Sludge	51.8	13.8	37.7
Coal lockhopper vent	3.5	2.3	4.2
Ash lockhopper vent	1.7	1.7	1.7

Source: 9

TABLE D-8. KOPPERS-TOTZEK GASIFIER STREAM FLOW RATE DATA

Stream	Flow Rate, g/s-gasifier
Inputs:	
Pulverized coal	1,750
Oxygen	1,640
Steam	175
Outputs:	
Raw gas (dry)	3,110
Slag	80
Discharge water	2,275
Fly ash (dry)	210

Source: 6

TABLE D-9. TEXACO GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier	
	Period One[a]	Period Two[b]
Inputs:		
Coal (dry basis)	1,690	1,634
Oxygen	1,564	1,561
Fresh water[c]	1,319	347
Demineralized water	1,424	1,278
Outputs:		
Scrubbed synthesis gas	3,221	3,206
Slag	570	501
Flash gas	7.5	8.3
Settler underflow-blowdown	2,141	1,029

[a] No recycle of clarifier underflow.
[b] Minimization of fresh water makeup by recycle of clarifier underflow.
[c] Includes water in coal feed, additive mixture, and flocculant mixture.
Source: 8